



Federal Ministry
of Defence

Military Scientific Research Annual Report 2020

Defence Research for the German Armed Forces



BUNDESWEHR

Military Scientific Research Annual Report 2020

Defence Research for the German Armed Forces

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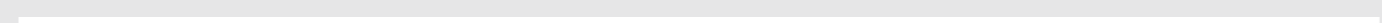
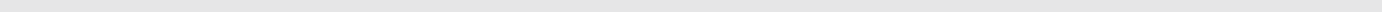
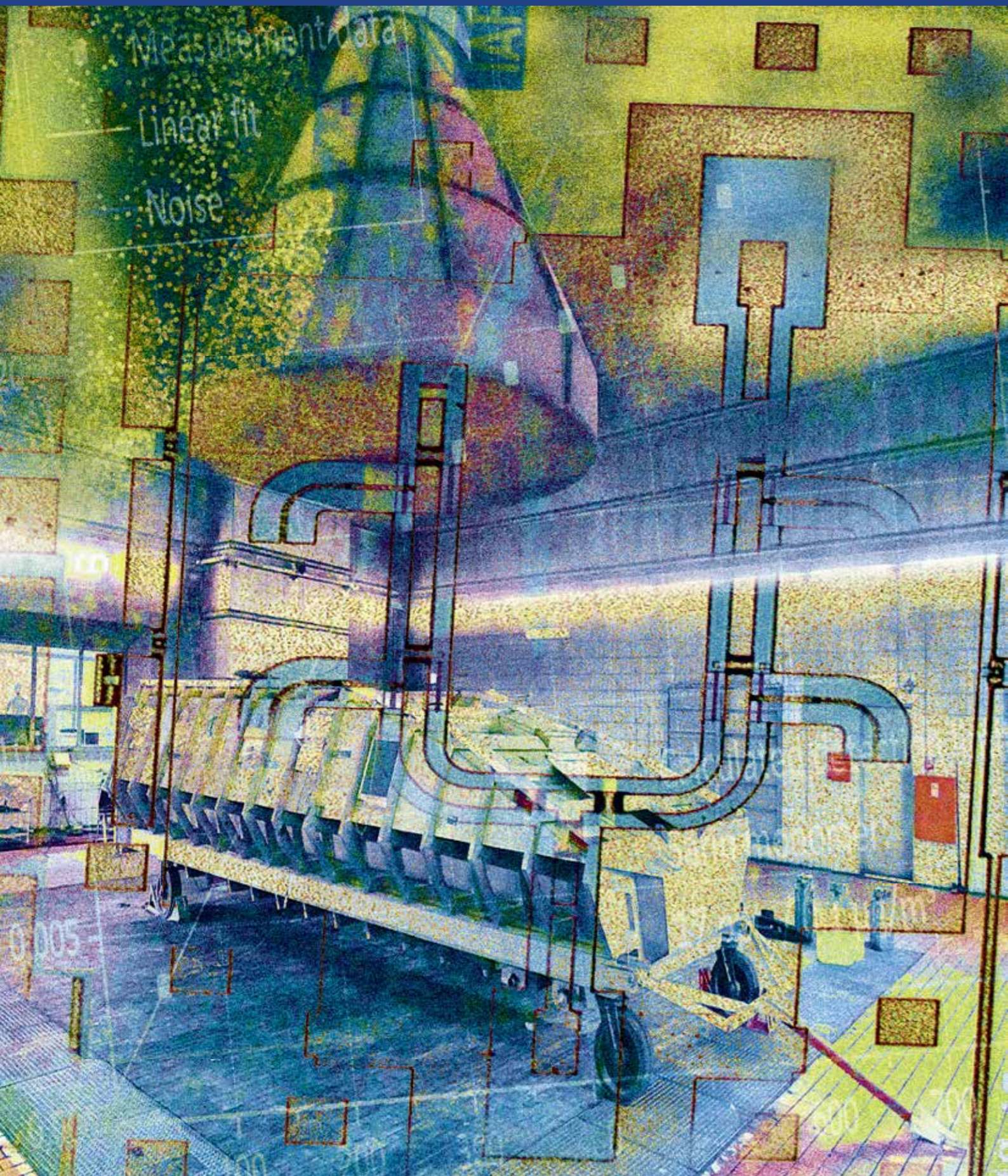
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Ministerialdirigent Ralf Schnurr

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Defence Research for the German Armed Forces

The security and defence challenges faced by Germany, the EU and NATO have increased in size, volatility and complexity in recent years.

Progress in the research and development of new technologies such as digital technology, artificial intelligence, unmanned systems, hypersonic technology, biotechnology, and cyber instruments will have a fundamental effect on security and defence systems of the future. The use of such technology in weapon systems will raise questions about their potential for destabilisation and their conformity with international law.

Space is becoming increasingly important for security policy. Like many other countries, Germany relies on free access to critical infrastructure in

space as well as on the peaceful and sustainable use and protection of this infrastructure. Satellites are of vital importance both in the civilian sector (for society, the economy, and science) and in the military sector (for intelligence, reconnaissance and surveillance and for navigation and communication).

The basic configuration of the Bundeswehr has capabilities, forces and assets for the following tasks:

- national and collective defence in a NATO framework and in accordance with the guidelines of the European Union
- cyber security/defence
- crisis and risk management for the protection of German nationals abroad
- home defence and host nation support
- activities in and from Germany in support of operations.

The Bundeswehr must be able to perform these tasks simultaneously and at any time.

All major organisational elements must work together to fulfil the tasks of the Bundeswehr. This is also the case when it comes to research in

- defence technology,
- military medicine and psychology,
- military history and the social sciences,
- the geosciences and
- cyber and information technology.

Selected examples of research in these areas will be presented in the following chapters.



Ralf Schnurr



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Defence Technology Research

The broad capability spectrum of the Bundeswehr makes it necessary to closely study and further develop all fields of science and engineering which are relevant to defence technology. This means we must examine civilian research findings and evaluate technological developments for their future military usefulness and threat potential.

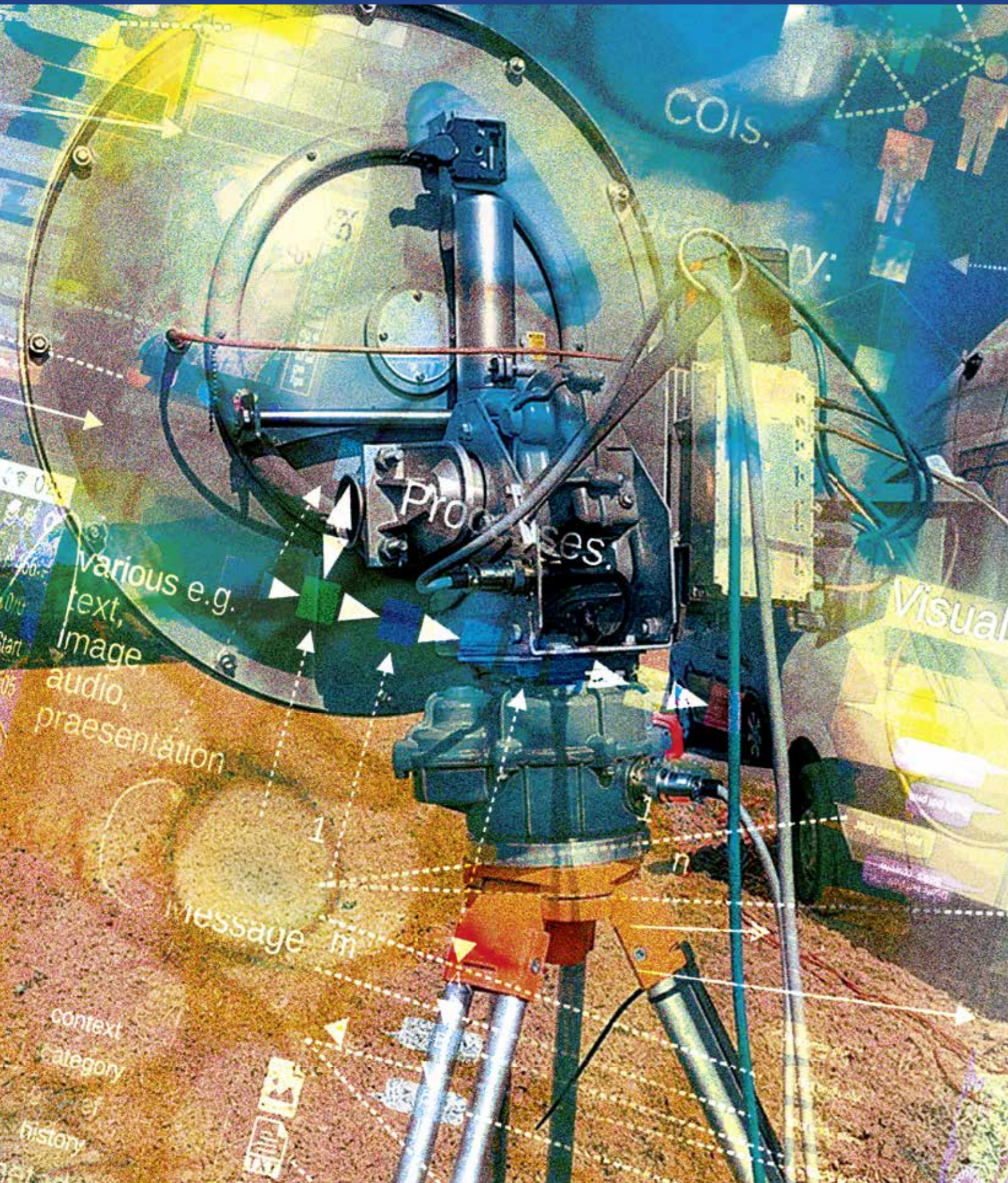
In order to enhance Bundeswehr capabilities, we must identify strategic fields of interest and swiftly develop relevant emerging technologies so that they are ready for production. We must also maintain and strengthen our own technological sovereignty in key national technologies.

The objective is to safeguard and improve the ability of the Bundeswehr to respond effectively by cultivating new ideas and rapidly implementing innovations. This will allow us to provide the Bundeswehr with the necessary equipment in good time.

In Germany, defence research and technology activities are conducted in three different ways:

- at Bundeswehr research institutes and technical centres,
- together with the Fraunhofer Society for the Advancement of Applied Research, the German Aerospace Centre, and the German-French Research Institute of Saint-Louis and
- by awarding research and technology contracts and grants to third parties, i.e. industry, universities and other institutes of further education, and non-university research institutes.

This chapter will present examples of defence research and technology activities conducted in 2020 in each of these three areas.



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Bioinspired camouflage assessment by calculating local conspicuity

Assessing the effectiveness of camouflage in advance is an important task when it comes to providing a unit with the greatest possible protection from detection and recognition. Observer experiments and mathematical models are often used for this purpose. In this work, neurophysiological principles are used to extend the models by biologically inspired signal processing.

The effectiveness of camouflage is best expressed by the extent to which detection, recognition, or identification (DRI) of platforms using these measures is delayed and reduced compared to differently or non-camouflaged units. To this end, observer trials are often used to directly analyse the effects of camouflage on human observers. Observer trials require both time and personnel, however, and human factors must be considered in order to make statistically meaningful conclusions afterwards.

This raises the question of whether it is possible to use mathematical models in image processing to predict how well signature-changing measures will affect DRI values. There are already many approaches to this, such as the signal-to-noise ratio or the statistical similarity of the texture of the object to the texture of the background. Although this is a good approach, these evaluations often ignore the transition from object to background, which is often a disruptive saliency that nevertheless gives away the well-camouflaged object.

In this work, focus is placed on neurophysiological signal processing. This is a promising approach, as it brings into

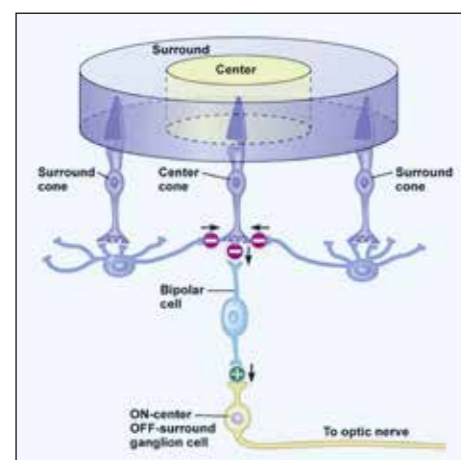


Fig. 1: Receptive field in the retina (source: Pearson Education, Inc., 2011)

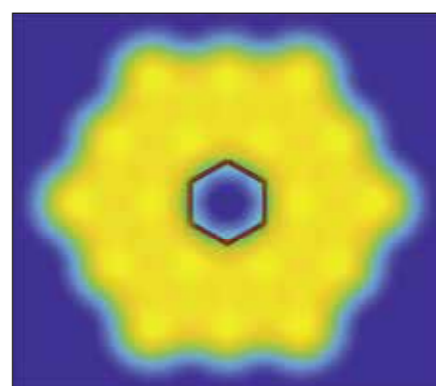


Fig. 2: A mathematical model of the receptive field as the core element of the saliency assessment model



Fig. 3: Application of the model to the image of a camouflaged shooter. Areas marked in red-yellow (left half of the image) correspond to areas of higher conspicuity. (source: Caters News Agency)

focus the actual neural processing of what is seen, and thus the processes that direct the observer's attention. With these findings, models can be extended to include the processes that direct the eye's gaze to areas of the image.

Since only the central area of vision is seen in detail (in the fovea), the eye scans the scene by making saccadic, rapid jumps of gaze focus, and the brain assembles the overall image from these jumps. The focus points of these jumps are determined by the brain through search patterns as well as through statistical discrepancies in the scene.

The search pattern determines the area to be searched and the order in which areas are searched. If something in the visual field is different, it is fixated and analysed and classified by higher neuronal processes.

This difference is detected by neuronal structures, i. e. the receptive fields. These transmit a nerve signal if there is a difference in the input signal between the central area and the outer area (Figure 1). This ranges from differences in brightness to the detection of alignment imbalances in the visual cortex, for example if an image is at an angle and therefore attracts attention.

Our model is inspired by receptive fields (Figure 2) and uses this form of anomaly detection for visual material. A wide range of biologically relevant parameters, such as contrast and spatial frequencies, are used. Since the camouflaged object is compared with its background and the model scans the image material completely, statistical discrepancies caused by conspicuous transitions from camouflaged object to background



Fig. 4: A road section with traffic signs (top) and associated conspicuity map (bottom)



Fig. 5: Thermal image of camouflaged objects and the corresponding conspicuity map, which reveals differences, effectiveness and flaws in the camouflage

are also detected in this way and are included in the signature evaluation (Figure 3).

The resulting conspicuity map (Figure 4) can now be used to determine camouflage measures such as the overall conspicuity of the object or the occurrence of a conspicuity peak on the object which could give it away despite otherwise good camouflage. In this way, problem areas (Figure 5) can be identified and possibly corrected. It is also possible to parameterise the amount of distraction that the environment provides, thus making the search for the object more difficult and delaying it.

It has been shown that this form of image processing can provide a reliable measure of camouflage assessment and that it can be further improved by comparison with actual observer performance.

Virtual reality and the efficient use of 3D data from optronic sensors

3D models can now be generated from the data of optronic sensors in a faster and better fashion, but it is difficult to use this data with current display systems. Virtual reality allows us to use this complex data more efficiently through immersive, stereoscopic display, but it must be appropriately integrated into existing workflows.

Due to new and improved sensor technology and post-processing capabilities, it is now possible to generate detailed, geo-referenced 3D models from the data of optronic sensors. This opens up new possibilities for the fields of intelligence, surveillance and reconnaissance (ISR).

Along with new opportunities and benefits, the three-dimensional representation of the real world also presents new challenges. For one thing, generating data is costly and, at least for the levels of detail required in some use cases, more obtrusive due to the need for close-up images. For another, processing three-dimensional data is complex and differs significantly from work with almost exclusively two-dimensional data.

Figure 1 contains an aerial photograph on the left which was taken almost vertically. On the right are four different oblique views of a 3D model of the same region. Although these views represent only a fraction of the total number of possible views, it is already apparent that the 3D model contains considerably more information, not including depth information, which



Fig. 1: Left: orthophoto, right: four different views of a reconstructed 3D model of the same region



Fig. 2: Virtual walk-through of a scene at a 1:1 scale of the data

cannot be represented here. New potential can thus only be exploited if suitable solutions are found both for the representation of large amounts of data and for the interaction with them.

VR can be used to eliminate the greatest discrepancy between the amount of available data and its representation. Stereoscopic visualisation makes it possible to convey a real impression of depth and thus to perceive three-dimensional data in a truly three-dimensional way. Provided that data quality is adequate, VR makes it possible to display data in its original size and thus to facilitate a virtual walk or even flight through a scene (Figure 2). By artificially limiting and scaling the viewed 3D space to a specific region, an overview is possible, which is particularly suitable for a joint viewing of data (Figure 3). Other participants can also be represented and an intuitive exchange between them is possible. Unlike in a real environment, it is possible in VR for users to work on the same data at the same time but to be in different display modes and to exchange information about them. Figure 4 shows one participant at the virtual table while another participant is on a virtual walk-through of data, using a virtual laser pointer to highlight a building. Furthermore, it is possible to take measurements and to display additional information (Figure 5).

Virtual reality enables these forms of visualisation and interaction through immersion, which is achieved primarily by spatial tracking of the person through their headset and controller. These represent a completely different form of input for most people today who are used to computer mice and keyboards. Since three-dimensional data is not yet ubiquitous and wearing a headset is not yet a permanent alternative to

a conventional workstation, it is important to ensure an easy transition between the different interaction options. Unlike in most VR games, the functionality of the mouse was therefore emulated for most functions with the controller. For this reason, basic operations at the desktop and in virtual reality are similar. This makes it easy to switch to the virtual world for tasks where this form of visualisation offers real added value.



Fig. 3: Cooperation on scaled, three-dimensional data



Fig. 4: Cooperation in different display modes

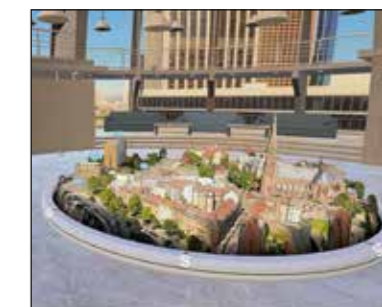


Fig. 5: Display of georeferenced meta-information

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Research on laser sources for optronic countermeasures and high-energy lasers

In the future, laser technology will play an increasing role in electronic warfare and protection, especially in short- and mid-wave infrared (SWIR, MWIR) for reconnaissance and optronic countermeasures (OCM) and for SWIR laser effectors. The Fraunhofer Institute for Optronics, System Technology, and Image Exploitation is conducting research on laser sources as a national key technology with relevance for the Bundeswehr and is focusing on critical components and technologies to ensure their accessibility.

The Institute is conducting research along the entire optronic chain from light sources (primarily lasers) through light transport, light conversion and image interpretation up to information processing. Research on power-scaled SWIR and MWIR laser sources for OCM and high-energy lasers (HEL) has been significantly extended in recent years and is currently taking place in four main areas: (1) laser materials and critical components for laser sources, (2) lasers for optronic countermeasures, (3) high-energy lasers and (4) numerical modelling and simulation. The first area focuses specifically on research on critical components to ensure technological accessibility.

The power scaling of SWIR fibre lasers and fibre amplifiers plays an important role in OCM in MWIR by the pumping of non-linear converters and as narrow-band sources for coherently coupled laser sources for HEL. Research is focusing especially on thulium (Tm)- and holmium (Ho)-doped active fibres and specific components such as high-power fibre end-caps for increasing the power handling capability of fibres and optimised beam quality at high-output powers (Figure 1). Up to 187 W under continuous operation in the 2050 – 2090 nm

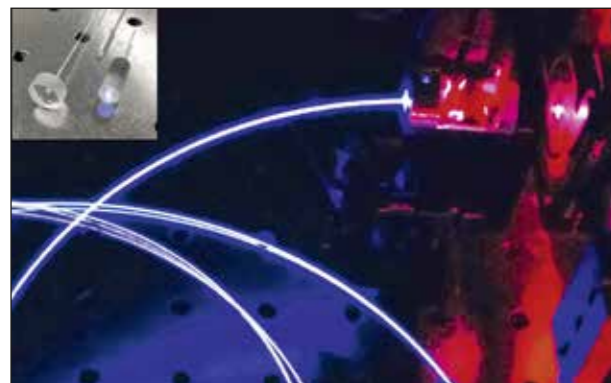


Fig. 1: Pulsed 2 µm fibre laser in operation. The inset shows different end-cap designs

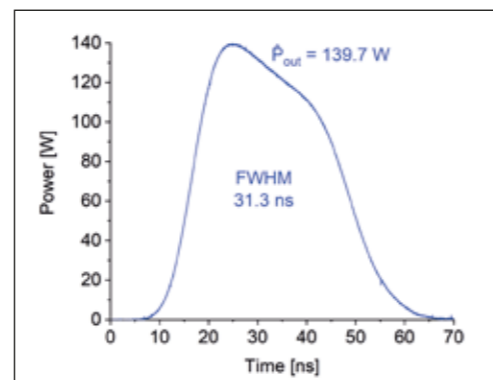


Fig. 2: Pulse power vs. time of a narrow-band 2.09 µm Ho³⁺:silica fibre preamplifier

range were achieved using a triple-clad Tm:Ho-doped fibre that uses a specific glass structure to avoid power limitations in double-clad fibres. This constitutes an important milestone for future power scaling for OCM and HEL. In pulsed mode, up to 0.8 mJ at 40 ns pulse duration were obtained – an almost twofold increase with respect to the prior state of the art. This is especially important for compact MWIR sources for novel OCM.

An important way to power scale HEL sources in the 2 µm wavelength range is the coherent coupling of multiple sources. This provides not only a resilient and robust construction but also the possibility of phase correction for atmospheric turbulence. For this reason, the Institute is conducting research on narrow-band single-mode Tm- and Ho-doped fibre amplifiers and their power limits, which are limited especially by non-linear effects. In a test setup using an Ho-doped preamplifier, our scientists achieved an amplification of > 1000 x with up to 140 W peak power without significant Brillouin scattering at < 20 pm of single-mode line width (Figure 2). Important parameters can be derived for the design of a narrow-band fibre laser source with > 10 kW peak power for OCM and > 1 kW continuous power for future investigations in coherent coupling for HEL.

In parallel to further experimental activities such as the investigation of nonplanar resonators for increasing the robustness and beam quality of lasers and optical-parametric oscillators (OPO) (Figure 3), the Institute is conducting research on numerical modelling and the simulation of fibre lasers, solid-state lasers and nonlinear converters to increase our understanding of fundamental physical processes and to optimise future designs and systems. New codes for the simulation of complex

fibre laser and amplifier topologies have been developed. Important advances in the simulation of laser resonators and OPO by field propagation have also been achieved, which in addition to laser dynamics and laser power calculate important parameters such as the expected beam quality of a given design (Figure 4). These new codes and models facilitate the effective design and optimisation of experiments and thus efficient research on complex laser designs.

Aside from fundamental research and the development of laser technology, these activities directly contribute to the analysis and evaluation capabilities of the Institute for the German Ministry of Defence.

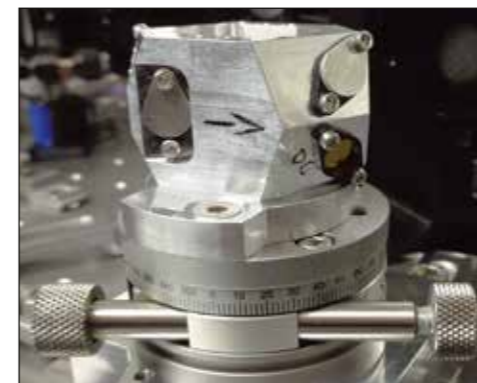


Fig. 3: Miniaturised FIRE resonator for increased robustness and beam quality of an OPO manufactured at the Institute

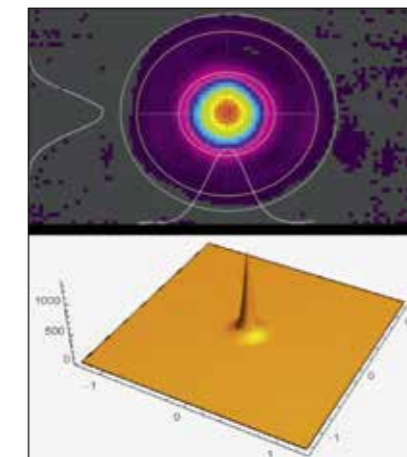


Fig. 4: Measured and simulated beam profile of a power-scaled 2.09 µm Ho³⁺:YAG laser

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Using virtual human models and biofidelic dummies to improve the safety of soldiers

Researchers at the Fraunhofer Institute for High-Speed Dynamics are evaluating the feasibility of using virtual human models and biofidelic dummies for military applications and the safety and security of soldiers. New capabilities are arising for assessing biomechanical processes in simulations and experiments. This can be seen in the dimensioning of ballistic vests for body protection.

Important pieces of personal protective equipment, especially ballistic vests, can be analysed in combination with the human body as one comprehensive system using numerical methods. During the design process, virtual human models allow us to study dynamic phenomena arising from projectile impact on body armour components. Such methods help reveal how highly dynamic processes and forces at lower strain rates can affect the human body. What is more, the risk of injury due to behind-armour blunt trauma (BABT) can be evaluated and assessed numerically.

The institute has established innovative hardware and sophisticated software tools to study such forces in experiments and simulations. Not only military but also civilian applications can be studied, including work safety, traffic accident analysis, and sports medicine.

Virtual human models are used in finite-element simulations in order to assess the effects of hits, collisions and impacts of intercepted projectiles (Figure 1). Such software models represent actual humans in detail, including not only the outer body

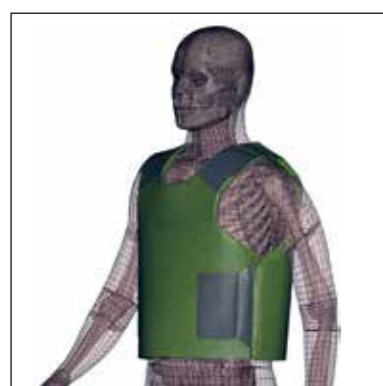


Fig. 1: Virtual human model GHMBC M50 with a ballistic vest in a donned configuration

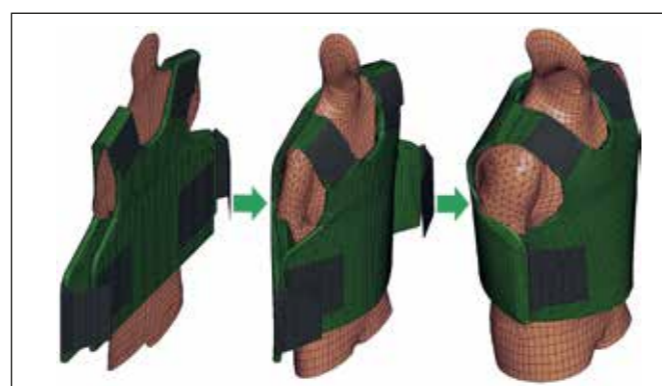


Fig. 2: Forming simulation of a FE vest model starting from a two-dimensional configuration and progressing to an arbitrary three-dimensional body contour for an application with a virtual human model

shape, but also bones, muscles, ligaments, tendons, and internal organs. They differ from mathematical models for crash-test dummies in the automotive industry as they are a direct representation of human tissue and not technical components of an anthropomorphic test device.

A further advantage is their universal applicability. They are not restricted to certain well-defined load cases, as are conventional crash test dummies and their numerical counterparts. A current challenge is the quick and efficient positioning of these models in an appropriate posture. The models are demanding when it comes to handling and the available computational resources. In addition, controllability and the mapping of various muscular activity states are current areas of research.

Last year, researchers at the Institute successfully developed a method for applying protective clothing and equipment directly onto the body of the wearer (Figure 2). This allows us to build simulation models that are capable of analysing personal protective equipment, i.e. ballistic vests, under virtual field conditions. This new method can help improve the design of protective equipment, identify potential weak points, and save the time and money required for physical experiments. The current focus of work at the Institute is on using computers to automatically process comprehensive simulation campaigns with varying input parameters in order to find answers to exactly these questions.

Biofidelic dummies, a new generation of anthropomorphic test devices, can be used to compare numerical results with experimental findings (Figure 3). These dummies were originally developed for pedestrian accident reconstruction and

have a wide and flexible range of application. Their failure limits have been specifically adapted to human requirements. If an external force acting on such a dummy exceeds a certain threshold – one at which a human would suffer severe injury like broken bones or torn ligaments – the dummy's components will fail accordingly.

Researchers at the Institute are currently evaluating possibilities to improve parts of such dummies in order to better assess potential injuries caused by blunt forces (Figure 4). This will allow us to analyse biomechanical loads for certain load cases in order to find appropriate measures for the protection and safety of soldiers on operations.



Fig. 3: Biofidelic dummy with a donned ballistic vest including special protection for the abdomen and neck

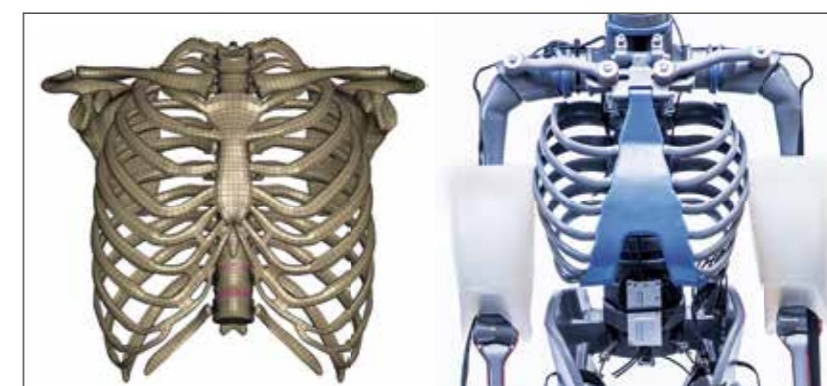


Fig. 4: Numerical and experimental representation of a human thorax for direct comparison. Left: Computer model (GHMBC M50, source: Elemance). Right: Hardware (Biofidel-Dummy Primus, source: Crashtest-Service.com GmbH)

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The potential of digitalisation for live-firing training at military training areas

The Fraunhofer Institute for High-Speed Dynamics is investigating modern, effective live-firing training at military training areas using sensors and methods of digitalisation. What are its characteristics and potential? How can safety be presented in a digital training environment and meet extended requirements compared to the current approach?

Combat training should prepare soldiers for missions in a realistic manner. For this purpose, they practice live firing in predetermined scenarios at military training areas. Targets, often pop-up targets, are thus far mostly static and analog controlled. A dynamic target presentation that is integrated into a digitalised future combat training system promise more complex scenarios for more intensive training.

A key question is what concepts and procedures can guarantee the safety of exercise participants and bystanders when modern technologies such as portable, self-moving or virtually displayed targets are used for effective training.

In order to minimise the risk to people inside and outside the training area during a combat exercise, a danger zone is defined for each exercise which takes into account the weapons and ammunition used and the planned sequence of the exercise. Range safety planning is still mostly manual. It is time consuming and not very flexible.

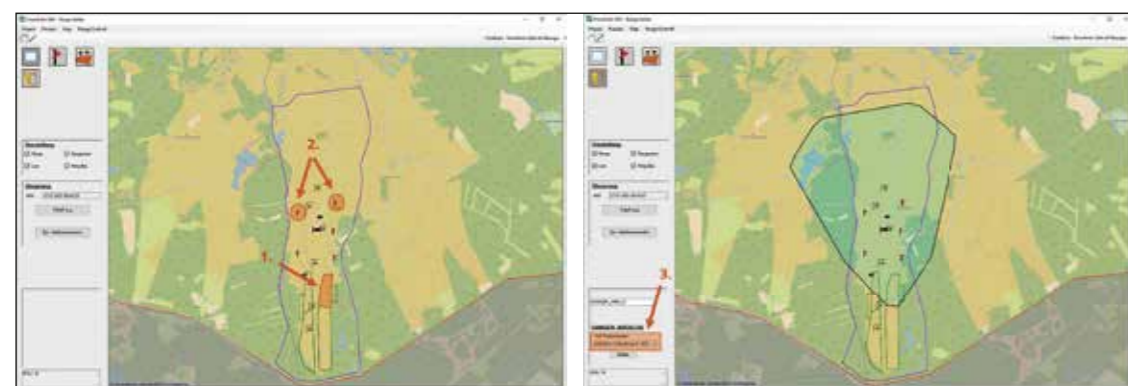


Fig. 1: Illustration of the process of interactive danger zone calculation with the Institute software tool for range safety planning using the example of shooting from a predefined firing zone with G36 and combat ammunition. The calculation only requires the selection of a firing zone, two limit-of-fire markers (left picture) and the specification of weapons and ammunition (right picture) in order to automatically determine the composite danger zone (turquoise area in the right image)

Computer-based methods, such as the software tool developed by the Institute for digital, regulation-compliant range safety planning, can considerably simplify this process and make it more flexible. The fast, partially automated calculation of danger zones, which can also be carried out on the shooting range using a tablet computer, allows input parameters to be changed quickly and makes it possible to plan even complex training scenarios. The inclusion of autonomously manoeuvring robot targets makes targets more dynamic and thus more challenging with respect to safety considerations. Tools used on site such as digital range safety planning or simulated training sequences can make a significant contribution to range safety.

During live firing, exercising soldiers may only shoot into an area that has been marked by limit-of-fire markers. Compliance with this requirement is monitored on site by range safety personnel who are individually assigned to exercising soldiers. This monitoring process would be drastically easier if the position and orientation of each handgun involved could be recorded in real time and automatically monitored during training.

At the Institute, plans for a corresponding sensor system have been developed and set up as a functional illustrator. The modular G36 grip was used as a basis and was retrofitted to soldiers' personal equipment for the exercise. For this handle sensor system, it has already been demonstrated in an exercise how the "live" position and orientation data of the weapon can be transmitted to a higher-level command and control system. The focus of current work is on increasing the technological maturity of the functional illustrator, taking into account safety requirements.



Fig. 2: First functional illustrator of a handgrip sensor system for recording the spatial orientation of a handgun using the modular G36 handle as an example

The above aspects are part of a concept for a future combat training system that combines range safety, exercise planning, exercise control and evaluation in a holistic approach. The collection and analysis of relevant exercise data, for example the position of the exercising soldiers and the targets, is just as important as feeding this information back into the training sequence in order to make training interactive and adapted to the situation. Initial practical experience with a combat training system developed for basic concept illustration at the Fraunhofer Institute for High-Speed Dynamics was gained in a live-firing training run together with partners from the Guard Battalion and the Fraunhofer Institute of Optronics, System Technologies and Image Exploitation at the Bundeswehr Wildflecken training area.



Fig. 3: On 1 October 2020, a test campaign with live firing took place at the Wildflecken military training area which used autonomously manoeuvring robot targets and a concept illustrator of a digitalised combat training system developed at the Fraunhofer Institute for High-Speed Dynamics. Following this successful training run, experts in the digitalisation of military training areas (from left to right: Dr. Siegfried Nau (Fraunhofer Institute for High-Speed Dynamics), Frank Jaspers (Bundeswehr Technical Centre for Weapons and Ammunition) and Brigadier General Andreas Henne (Bundeswehr Territorial Command, Project Manager of the Further Development of Bundeswehr Training Areas and Ranges) answered questions from Lieutenant General Martin Schelleis, Chief of the Joint Support Service, and an interested expert audience

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Miniaturised millimetre wave SAR for small airborne platforms

MIRANDA35 is a high-resolution radar system developed at the Fraunhofer Institute for High-Frequency Physics and Radar Techniques for airborne intelligence, surveillance and reconnaissance (ISR). The system was miniaturised for use on small airborne platforms, and its performance was increased significantly. In a flight measurement campaign with an ultralight aircraft, the changed configuration was evaluated and SAR data was obtained in various measurement modes.

The use of small unmanned aerial vehicles (UAV) for medium-range surveillance and reconnaissance will likely become more important for the Bundeswehr. The sensors (EO/IR) currently available for such platforms are, however, highly dependent on the time of day and the weather, which poses a significant problem.

With further miniaturisation and increases in the performance of radar sensors in the millimetre wave range, the use of imaging radar (synthetic aperture radar, SAR) will also be feasible on small airborne platforms. The above-mentioned problems do not apply to imaging radar. They can therefore be used as a supplementary or sole sensor on such platforms. The use of SAR systems in the millimetre wave range has been studied for many years at the Institute, and the construction and further development of MIRANDA demonstrators is continually being pushed forward.

The SAR system MIRANDA35-4Rx was designed for airborne ISR on manned flight platforms and UAVs. The 35 GHz sensor has an output power of 10 W and is suitable for altitudes of



Fig. 1: MIRANDA35-4Rx system in the wingpod of the Delphin ultralight aircraft. The four receiver antennas (left) and the transmitting antenna (right) of the radar front end can be seen



Fig. 2: Take-off of the Delphin ultralight aircraft at Mönchsheide airfield with MIRANDA35-4Rx integrated in the new wingpod



Fig. 3: Ground control station with telemetry antenna south of Bad Breisig during the 2020 measurement campaign with the Delphin ultralight aircraft

up to 3000 m. For interferometric and polarimetric measurement modes, the radar system was equipped with four receive channels, which makes possible, for example, ground moving target indication (GMTI). The bandwidth of 1.5 GHz allows a distance-independent resolution of up to 10 cm and facilitates the detection of even very small structures. The radar front-end, the associated backend, and the required software were designed and built at the Institute in cooperation with Armassuisse. The system was continuously developed over several years and has been successfully integrated into the Swiss Centaur aircraft, a modified DA-42. Its functionality has been extensively tested in numerous flight measurement campaigns.

A special feature of the MIRANDA systems is the real-time processing on board the platform, which is based on a fast SAR algorithm developed at the Institute. The processed SAR images (Quicklook) and the most important system parameters are transmitted live to the ground station via a bidirectional data link.

In 2020, the volume and weight of the four-channel sensor system were significantly reduced, thus enabling the system to be integrated into the small Delphin carrier platform (the Institute's own ultralight aircraft, UL). This was achieved through a new, compact design in which cable and waveguide lengths in particular were shortened. This also led to a reduction in power losses and noise, so that overall system performance was increased. A particular challenge for small (more unstable) flight platforms is the increasing demands on motion compensation. This fact was taken into account through optimised post-processing of IMU motion data (inertial measurement unit) and its integration into offline SAR processing.



Fig. 4: Polarimetric SAR image (red: co-polar, green: cross-polar) of the Mönchsheide airfield

Figure 1 shows the MIRANDA35-4Rx in the wingpod under the wing of the UL, with the four receiver antennas (left) and the transmitting antenna (right).

A flight measurement campaign was carried out with the revised system in autumn 2020. Figure 2 shows the UL at Mönchsheide airfield. The focus of SAR measurements was on several research topics: change detection, GMTI, 3D imaging, urban infrastructure and polarimetric SAR. A total of 75 flight tracks with different measurement modes were flown at different locations. Figure 3 shows the ground station, from which the flight measurements were controlled and managed. Measurement data are currently being processed and evaluated for the further development of the system and algorithms. Figure 4 shows a polarimetric SAR image of the Mönchsheide airfield during a calibration measurement.

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UAV-based neutron and gamma detection utilising novel scintillation materials

The detection of radiation is important for the safety of personnel and the assessment of situations that include radiological threats. Research in the field of detection materials and the development of novel scintillators has made possible an improved detection capability for airborne radiation surveillance due to the simultaneous detection of neutron and gamma radiation.

Growing uncertainties around the world are moving countries to upgrade their military equipment and to modernise their weapon arsenals. This also applies to states that possess nuclear weapons or that are suspected of pursuing them. This worldwide development has led to an increase in the danger of the use of nuclear weapons, which is why we must prepare for various deployment scenarios.

At the same time, developments in the field of protection for deployed military personnel and civilians is ongoing, including the development of radiation detectors. These innovations have led to technology that can be used to protect personnel in the exploration and assessment of threat situations, e. g. by utilising unmanned aerial vehicles (UAV). UAV can be used for airborne visual situation identification but also for assessing radiological threat situations if they are equipped with appropriate radiation detectors.

The weight and size are limiting factors when it comes to the selection of potential radiation detectors for mounting on a UAV. The detection capability of a radiation detector depends



Fig. 1: UAV can be used for large-area, airborne radiation surveillance (source: Pixabay.com)

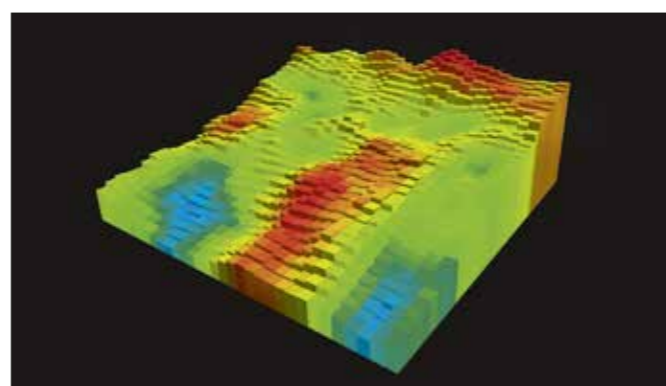


Fig. 2: Example of a heat map summarising measured radiation (source: Shutterstock.com)

heavily on its intrinsic efficiency and its detection volume. The higher its intrinsic efficiency and the larger its detection volume, the more accurate is the measurement result and the smaller is the threshold over which elevated radiation is detectable.

There are two types of radiation that are relevant for assessing radiological situations: neutron radiation and gamma radiation. With ordinary detection materials, these two types of radiation require two separate detectors, one for each type. This is important when it comes to weight limits of the UAV. There are already commercial detection systems that have two detector systems and that are designed for use with a UAV. Because of weight limitations, these generally have small detection volumes, with a correspondingly smaller detection capability.

Developments in the field of detection materials allow us to simultaneously detect neutron and gamma radiation using only one detection material. These novel materials are especially useful in applications where the size or weight of a radiation detector is limited.

The Bundeswehr Research Institute for Protective Technologies and CBRN Protection and the Fraunhofer Institute for Technological Trend Analysis are currently developing a demonstrator of a detector system for airborne radiation surveillance which uses CLYC:Ce ($\text{Cs}_2\text{LiYCl}_6:\text{Ce}$) scintillation material. The CLYC:Ce scintillator can be used to detect both neutron and gamma radiation, while allowing signal separation via pulse-shape analysis. With regard to use with a UAV, this project considers signal acquisition and evaluation and optimises weight. For example, it uses silicon photomultipliers to convert scintillation

light into an electrical signal instead of the more common photomultiplier tube.

With novel scintillation materials, the development of airborne radiation surveillance is ongoing. Developments are based on the reduction of detector components on account of the simultaneous detection of neutron and gamma radiation in a single detection material. The resulting reduction in detector units leads to an increased detection capability with a constant weight and maximum detection volume.



Fig. 3: Test of silicon photomultiplier electronics with an NE102A scintillator

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Defence technology foresight in an international context in support of long-term R&T planning

The Fraunhofer Institute for Technological Trend Analysis is conducting technology foresight on long-term technological developments for the Bundeswehr and thus contributing to R&T planning. By contributing findings to international discussions on future technologies and military capabilities, the Institute can evaluate its own research and the technological findings of other nations for the benefit of national R&T planning.

The defence technology foresight business unit at the Institute is devoted to technology-oriented foresight for the area of responsibility of the Federal Ministry of Defence. Its central product is the Defence Technologies Forecast, which contributes to the analysis and assessment capability of the Ministry and the Bundeswehr with a quarterly analysis of technologies and future concepts (for more detailed information, see the article “Technology foresight in support of long-term R&T planning” in the 2018 annual report).

When it comes to support for decision-making regarding the long-term planning of defence R&T, there are a large number of players in the EU and NATO which are involved in R&T futures analysis and are thus contributing to its further development. Within this community, the Institute has evolved into a well-established, connected and sought-after player in the field of technology foresight.

The Institute regularly participates in EDA’s Technology Watch & Foresight Network and its workshops, where it contributes to the exchange of methodological best practices, including the

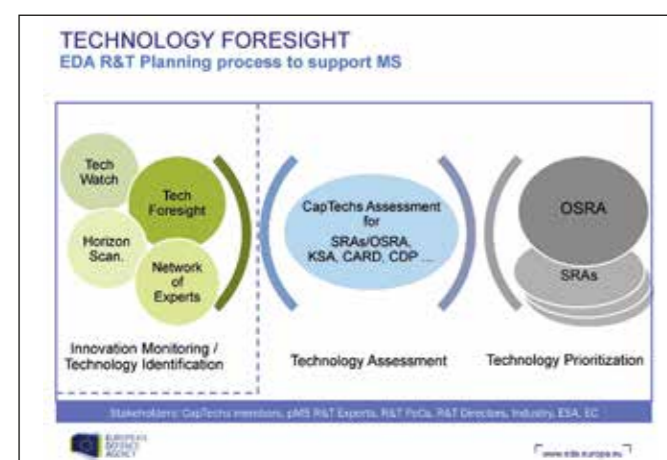


Fig. 1: Technology foresight in EDA’s R&T planning process (CapTech: EDA capability technology groups; SRA: strategic research agendas; OSRA: Overarching Strategic Research Agenda; KSA: key strategic activities; CARD: Coordinated Annual Review on Defence; CDP: Capability Development Plan, pMS: participating member states) (source: EDA)

question of how technology foresight can support the R&T planning of the member states of EDA (Figure 1). In addition, it occasionally contributes to EDA’s Working Group on Critical Defence Technologies on behalf of the Federal Ministry of Defence. Finally, the Institute, together with its Spanish cooperation partner Isdefe, has been supporting the implementation of technology foresight activities in EDA since 2015, which are financed by the operational budget of EDA, by conducting technology foresight workshops on selected technologies.

In 2020, NATO published a report entitled “Science & Technology Trends: 2020-2040”, which addressed current as well as emerging and disruptive technologies such as artificial intelligence, robotics and hypersonic weapons, and predicted their expected development. Here as well, the Institute was invited and active in preparatory workshops at NATO (Figure 2). It has also been active in the development of foresight methods in NATO-STO Research Task Group SAS-123 “Futures Assessed alongside Socio-Technical Evolutions” since 2016, as well as with Allied Command Transformation in their workshops on strategic foresight analysis for NATO.

Two senior scientists at the Institute have been members of the Independent Scientific Evaluation Group (ISEG) of NATO’s Science for Peace and Security research programme since 2016. This programme promotes scientific research, technological innovation, and the exchange of knowledge between NATO member states and partner nations. ISEG’s main task is to assess research project proposals and to provide expert support for research activities. With these appointments, the Institute has gained in-depth insight into technology-driven NATO activities, which contributes to its technological future situa-

tion picture and its knowledge about relevant international actors in R&T and which benefits national R&T planning.

This international network and shared assessment of technological developments of relevance for armed forces provides the Institute and thus the Bundeswehr with external quality assurance through the evaluation and elaboration of methods and results in technology foresight. The Institute has thus successfully established an interface between national and international foresight activities in defence and, through active participation in these bodies, has enhanced its ability to analyse the international R&T landscape for the Bundeswehr and to identify the importance of non-technological aspects such as the ethical, legal and societal implications of new technologies.



Fig. 2: NATO-STO report “Science & Technology Trends 2020-2040” (source: NATO)

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Diamond-based quantum sensing for RF signal analysis

Rapid progress in quantum technology will foster a number of military applications in the near future. For example, nitrogen vacancy centres in diamonds can be used to intercept and analyse complex and fluctuating radio frequency (RF) signals in real time. Such sensors are of key importance for electronic intelligence (ELINT) and the localisation and identification of radar sources.

The passive interception, localisation and tracking of rapidly fluctuating RF signals, which are used in modern communication and radar systems, requires real-time bandwidths of several GHz in combination with sub-ms time resolution. This is necessary in order to analyse time-frequency dependence and to classify the signal source. An example of a Bundeswehr ELINT platform is the Oste intelligence collector shown in Figure 1. Further examples are radar warning receivers in aircraft which can determine the distance, direction, speed and type of threat from intercepted radar waveform parameters.

Contemporary signal analysers are limited to a real-time bandwidth of approximately 100 MHz due to their A/D converters and the time necessary for computing the fast Fourier transform. Heterodyne downconversion is an additional approach with wide spectral coverage. It lacks, however, the required detection probability as well as real-time capability for the detection of pulsed signals.

For this reason, neither technique fully satisfies ELINT requirements. Active electronically scanned array and frequency-modu-



Fig. 1: Oste intelligence collector with ELINT capabilities (source: Bundeswehr/Björn Wilke)

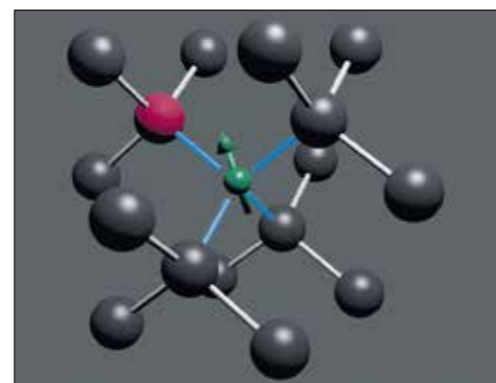


Fig. 2: Nitrogen vacancy centre in diamond with S=1 electron spin (source: FhG IAF)

lated continuous wave radars in particular are difficult to intercept and analyse with current techniques.

For military uses, quantum sensing (QS) is of particular interest. QS is capable of measuring physical quantities with unprecedented accuracy and dynamic range and low noise. The Fraunhofer Institute for Applied Solid State Physics is researching quantum sensors based on nitrogen-vacancy (NV) centres in diamonds due to their high technological potential, robustness, capability for integration, and room temperature operation (Figure 2). For magnetometry, such sensors are already capable of measuring static magnetic fields with $\text{pT}/\sqrt{\text{Hz}}$ accuracy at room temperature in conjunction with high spatial resolution. In such applications, optically detected magnetic resonance spectroscopy (ODMR) is used to measure unknown static magnetic fields.

With a known static magnetic field however, this technique can be used to determine the frequency and amplitude of unknown RF signals. The ODMR technique can thus be used to detect and analyse the spectral components of RF signals in the optical spectral range using high-performance, commercially available line cameras. This technique is therefore well suited to analyse complex and agile radar and communication signals.

Due to their high spatial resolution, diamond-based quantum sensors allow almost unlimited parallelisation. An extended NV ensemble embedded into a single diamond sensor chip allows the integration of hundreds of independent frequency channels. These are excited with a distributed green laser focus (Figure 3). The frequency spectrum is directly derived from the spatial distribution of the excited red luminescence (insert Figure 3)

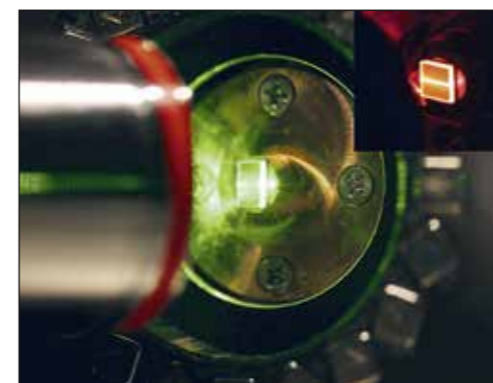


Fig. 3: Optically pumped RF diamond sensor chip and red NV photoluminescence (insert upper right) (source: FhG IAF)

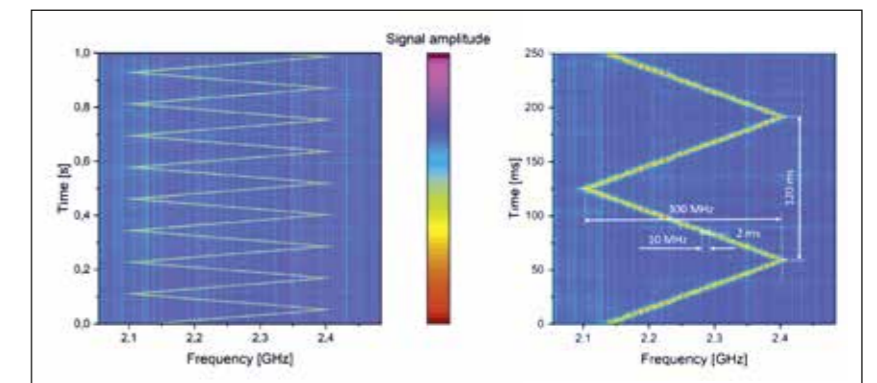


Fig. 4: Spectrogram of an FMCW-like RF signal (left diagram). A zoom of the time scale (right diagram) reveals a 300 MHz frequency modulation composed of individual pulses with 2 ms dwell time and 10 MHz frequency interval

without further signal processing. At the Institute, a real-time bandwidth of more than 1 GHz has been demonstrated while the frequency band can be set in the 0.7 – 6 GHz spectral range.

A high sensor readout rate is required for the time-frequency analysis of agile RF signals in real time. High-speed cameras allow parallel readout with refresh rates of less than 100 μs . The upper part of Figure 4 shows the spectrogram of a FMCW radar signal in the S band with a frequency modulation of 300 MHz. The technical parameters and thus the signature can be directly determined from the spectrogram. A magnification of the time scale shows that the signal is composed of individual pulses with 2 ms dwell time and 10 MHz frequency interval. These signature parameters can be used to classify the radar source or to prepare specific countermeasures.

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Efficient gallium nitride-based millimetre-wave integrated circuits

Integrated circuits with high power-added efficiency (PAE) levels are essential components of next-generation millimetre-wave transceiver systems. The functionality of monolithically integrated millimetre-wave integrated circuits (MMICs) for the frequency range above 20 GHz can be significantly improved by the integration of power amplifiers (PAs), low-noise amplifiers (LNAs), and switches and mixers.

The millimetre-wave frequency range above 20 GHz is becoming more and more attractive for digital links in military communication systems in order to meet the increasing demand for high data transfer rates. It is also vital for practical system solutions to reach high output power levels with low power consumption. Such requirements can be met by using gallium nitride-based monolithic millimetre-wave integrated circuits. For this reason, these circuits are a focus of research activities at the Fraunhofer Institute for Solid State Physics.

Due to the complexity of employed signals (e.g. LTE) in modern wireless communication applications, high efficiency can no longer be achieved at peak output power of the PA. Instead, equally high efficiency levels at moderate-drive conditions, corresponding to high output power back-off (OPBO) levels, are considered to be more critical in a real-world scenario to maximise the total system efficiency. The requirement of higher back-off efficiency has driven the development of more complex PA architectures such as the Doherty PA. By using a comprehensive load-modulation technique, the Doherty approach makes possible almost maximum PAE at a significantly higher

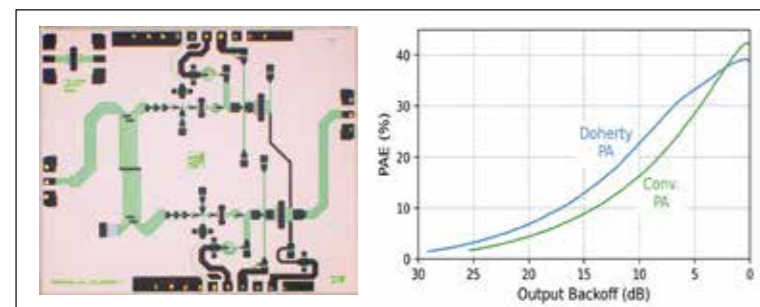


Fig. 1: 26 GHz GaN Doherty PA (left) and its corresponding efficiency performance with respect to OPBO (right) depicted in blue. In comparison, the green curve shows the efficiency of a conventional PA

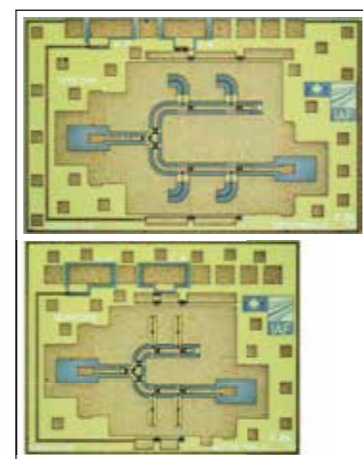


Fig. 2: D-band (above) and H-band (below) single-pole double-throw GaN switch MMICs

OPBO, as opposed to conventional approaches. The Institute has expertise in the design of such efficiency-optimised millimetre-wave power amplifiers in Doherty architecture and in the demonstration of monolithically integrated circuits. As depicted in Figure 1, more than 35 % PAE at 4 dB OPBO at 26 GHz with a peak output power of 3 W has been demonstrated with a GaN-based Doherty PA.

The measured PA values have an up to 10 percentage point PAE advantage over conventional class AB amplifiers with a comparable chip size (typically 3 mm x 3 mm). As further examples of GaN MMICs, single-pole double-throw switches designed with the Institute's GaN technology for operation in D-band (170 GHz) and H-band (220 GHz) are shown in Figure 2.

As far as system performance is concerned, the capability of on-chip integration of the individual components has a tremendous impact on total power efficiency as well as area efficiency. An analogue front end is considered to be a prime example of integrated millimetre-wave circuits which comprise PA, LNA, and switch building blocks. The combination of these components makes the bidirectional transmission of communication signals possible with a single chip. Thanks to recent developments, GaN-based technologies are catching up with silicon-based technologies in terms of monolithic integration.

The Institute is able to make fully integrated analogue GaN front end and mixed-signal circuit solutions for various high-data-rate wireless communication applications. The photograph of an E-band (71 – 86 GHz) GaN analogue front end MMIC is shown in Figure 3. It takes advantage of the high power capabili-

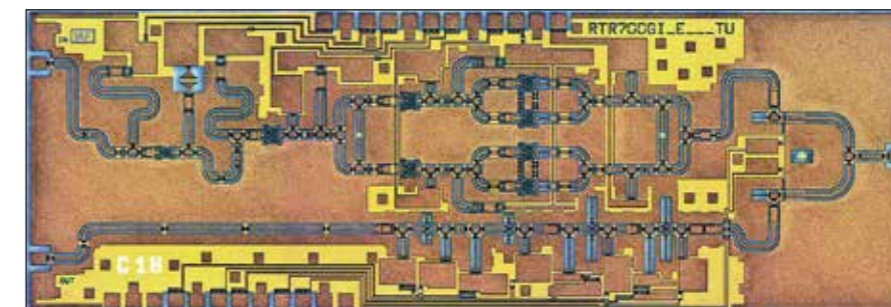


Fig. 3: Photograph of the first fully integrated E-band analogue front end GaN MMIC

ty of GaN PAs and switches and is equipped with a powerful GaN LNA, which is a key component of next-generation millimetre-wave transceiver systems.

The front-end chip is compact in size, with dimensions of 4.5 mm x 1.5 mm. When it comes to high frequency performance, a peak output power of 500 mW and a noise figure of less than 4 dB are expected on the basis of simulation results. In particular, a chip width of only 1.5 mm makes possible the use of front-end circuits in phase-controlled antenna arrays, where multiple components are used in parallel to realise analogue beamforming. Figure 4 shows a potential platform for GaN MMICs which has been developed by the Institute for military communication applications.



Fig. 4: Possible deployment scenario in communication applications for the GaN-MMICs developed by the Institute (source: FHS Förder- und Hebesysteme GmbH)

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Real-time evaluation of radio communication systems on different protocol layers

The Bundeswehr requires state-of-the-art, network-compatible radio communication systems for future-oriented mobile tactical communication. The Multi-Layer Simulator was developed in collaboration with the Bundeswehr Technical Centre for Information Technology and Electronics in order to support the evaluation of such systems through a realistic replication of radio channels in the laboratory.

A comprehensive and interoperable communication network at the mobile tactical level is vital for military units of the Bundeswehr. Currently used systems do not, however, meet the requirements for end-to-end IP-based (Internet Protocol) communication and can only be integrated with considerable effort. The Digitalisation of Land-Based Operations programme is designed to close this capability gap through the procurement of state-of-the-art network-compatible radio communication systems. A thorough analysis of different systems in the laboratory is crucial, in addition to field testing. Laboratory assessments must emulate as realistically as possible the conditions under which the systems will be used.

This is a complex task when it comes to MANET-capable systems (mobile ad-hoc network), which are state-of-the-art for the V/UHF band. A MANET is typically composed of a large number of links between nodes. The correlation between these nodes also has to be considered. In addition, radio channel conditions in mobile networks are constantly changing.

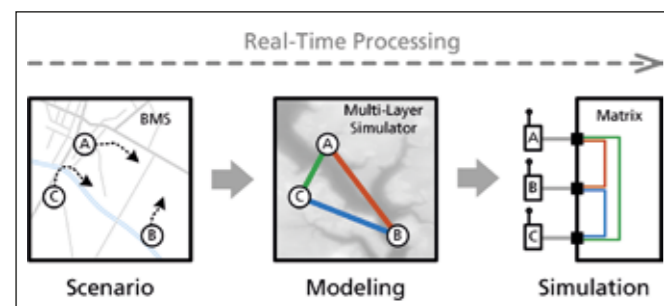


Fig. 1: A scenario defines the time-dependent positions of the nodes (e. g. using a battle management system). The Multi-Layer Simulator then computes in real time the channel properties of the links. A connection matrix sets the links between the tested devices accordingly

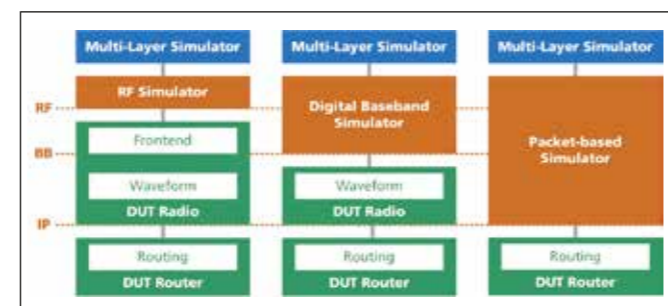


Fig. 2: Depending on the connection matrix used, consistent tests on different layers (RF – radio frequency, BB – baseband, IP – Internet Protocol) can be performed. The Multi-Layer Simulator provides channel properties for all cases

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The Fraunhofer Institute for Integrated Circuits and the Bundeswehr Technical Centre for Information Technology and Electronics have developed the Multi-Layer Simulator (MLS), which calculates the channel properties of the links in a MANET depending on the position data of the nodes and the desired simulation parameters. This is done in real-time, which allows the MLS to be used in a test setup with a dynamic generation of position data (using a battle management system or scripted events, for example).

The task of the MLS in a simulation chain is shown in Figure 1. The MLS receives the position data of the nodes in the scenario, performs modelling of the radio channels between the nodes, and forwards the channel properties to the connection matrix. This matrix then sets the links between the devices being tested, e. g. radios.

Different applications for this concept are shown in Figure 2. The left column shows a test in which radios are connected using an RF (radio frequency) simulator. The analysis is performed on the analogue RF layer. The middle column shows a test of radios without an analogue frontend, for example, an SVFuA processing unit. These are connected using a digital baseband simulator. The device being tested, in this case the processing unit with the waveform, is analysed on the base-

band layer. In the right column, the transmission link including frontend and waveform is simulated in a packet-based simulator. This allows routing protocols to be evaluated using a large number of nodes. The analysis here is performed on the IP layer. This approach allows consistent tests to be carried out on different layers (RF, baseband or IP) depending on the connection matrix used (analogue RF simulator, digital baseband simulator, or packet-based simulator). The channel properties are provided by the Multi-Layer Simulator in all cases, hence the term multi-layer.

Figure 3 shows the MLS in a typical testbed together with a position data generator and different connection matrices for the evaluation of radio communication systems.



Fig. 3: Testbed for the real-time evaluation of radios consisting of the tested devices, the Multi-Layer Simulator with connection matrices, and position data generation (from left to right – source: Fraunhofer IIS/Paul Pulkert)

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Fire protection and ammunition: Concepts for improving safety

The packaging of ammunition offers only limited protection against fire and heat. After a short time, the internal temperature reaches a critical value and the propellants and explosives react. In order to improve the fire protection of ammunition, we are investigating the use of intumescent fire protection coatings in different protection concepts in bonfire tests.

Ammunition must be transported and stored in such a way as to minimise dangers. While structural measures can ensure protection when in storage, this is not possible during transportation on ships, trucks and airplanes. Fires can result from technical defects, accidents or attacks. Soldiers are exposed to the latter particularly in asymmetrical conflicts on missions abroad, where attacks can be carried out with simple means such as IEDs or car bombs.

While there are established standards for fire protection in the civil sector, there are no similar regulations in the military sector for protecting ammunition from fire. Ammunition is only classified based on its behaviour in cook-off tests. There are no evaluations of elapsed time or the protective effect of packaging.

Intumescent fire protection coatings are widely used in the construction sector. When exposed to heat, an insulating foam develops and protects the substrate from the heat of a fire. The Fraunhofer Institute for Chemical Technology has developed such coatings for use on wooden substrates and for the thermal protection of ammunition. Two protection concepts were



Fig. 1:
Bonfire test



Fig. 2: Burning
ammunition box
made of wood



Fig. 3: Ammunition box with outer packaging
(uncoated)

examined: (1) the direct coating of ammunition boxes made of wood and metal and (2) the coating of wooden outer packaging containing the original ammunition box.

To compare the different protection concepts in realistic fire scenarios, bonfire tests (Figure 1) were carried out on both coated and packaged ammunition boxes made of wood and metal. Uncoated boxes (Figure 2) were also examined for as a control group. The outer packaging (Figure 3) consisted of a simple wooden box that was coated with a fire protection coating similar to the ammunition boxes.

As expected, the internal temperature of the uncoated metal box increased rapidly (Figure 4). A few minutes after the wood was set on fire, the internal temperature reached the critical value of 200 °C, at which ammunition is likely to explode. The coated metal box initially behaved similarly. However, once the insulating protective foam was formed (Figures 4 and 5), the internal temperature briefly rose to just below the threshold value and then fell to 120 – 150 °C, until the protective layer failed after approximately 30 minutes. A comparable protection time with a significantly lower temperature profile is achieved by employing the outer packaging.

The temperature rise (Figure 4) in the wooden ammunition box was similar to that in the metal box, but it occurred after a certain delay. The coated and packaged ammunition boxes showed very low internal temperatures. The ammunition was exposed to a temperature of below 100 °C for about 35 minutes and remained therefore at a temperature that is uncritical for most types of ammunition. It took 40 – 50 minutes before an internal temperature of 200 °C was reached.

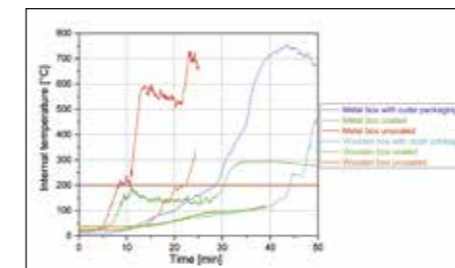


Fig. 4: Temperature profiles inside
ammunition boxes



Fig. 5: Protective foam formation during
bonfire test



Fig. 6: Metal ammunition box after
bonfire test

Instead of a simple outer packaging, universally applicable and modular outer packaging concepts have been developed which are compatible with the euro pallet format. Fire protection concepts for such packaging have been evaluated. The advantages of such modular concepts are the reusability of the outer packaging and the fact that the ammunition box does not increase in weight.

Fire protection coatings can enhance safety in the event of a fire or an increase in temperature by extending the time until an incident occurs or, in the case of a limited fire scenario, by completely preventing the ammunition from igniting. With wooden ammunition boxes, studies have shown that comparable protective effects are achieved by direct coating and by coated outer packaging. With metal ammunition boxes, coated outer packaging has clear advantages over direct coating.

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The use of microreactors for the safe and efficient production of energetic materials

The use of continuous microprocess technology in chemical synthesis and production offers special control of key process parameters, enhanced process safety, and potential access to new process windows. Despite low amounts of reaction mass, high and especially scalable throughput can be achieved in the synthesis of energetic materials.

High performance but low thermal and mechanical sensitivity have always been substantial requirements for energetic materials such as explosives, energetic binders, and plasticisers. National and international regulations are increasingly calling for the replacement of substances that are harmful to the environment and human health. The production and evaluation of new energetic components therefore remain important issues in explosives research as innovative chemical process engineering methods offer significant improvements in terms of process intensification and safety.

At the Fraunhofer Institute for Chemical Technology, continuous process technologies based on micro-process engineering are being developed which use microstructured reactors. These reactors consist of one or a multitude of parallel flow channels with lateral dimensions ranging from a few hundred micrometres to a few millimetres (Figure 1). The small channel dimensions combined with the resulting large specific surface area allow highly exothermic reactions to be carried out under thermally controlled conditions. The same applies to mixing-sensitive reactions with greatly improved mass transfer.



Fig. 1: Micro-structured glass reactor with passive mixing elements



Fig. 2: Laboratory set-up for reaction screenings in microreactors with embedded spectroscopic process analysis using fibre optics

The advantages of micro-process engineering can be particularly exploited for processes that can be highly hazardous, such as explosives synthesis, in order to dissipate strong reaction heat, to suppress side and decomposition reactions, and to safely process toxic, explosive and otherwise unstable products and intermediates in small reactor volumes and with residence times.

Microreactors can even be used in small facilities such as laboratories for the purpose of effective and safe reaction and process screening, especially in combination with spectroscopic and calorimetric process analytical techniques. To this end, processes are monitored in various spectral ranges (UV, Vis, NIR, IR, Raman) with high temporal and spatial resolution (Figure 2). In this way, various process conditions can be investigated within a short time and can be optimised with regard to variables such as reaction yield, selectivity and productivity.

Based on laboratory experiments, micro-process engineering makes it possible to rapidly increase production capacities. This can be achieved to a certain extent by increasing channel dimensions or by parallelising reaction channels, which can minimise difficulties usually encountered during scale-up in traditional reaction technology. At the Institute, for example, a microreactor plant has been developed which for several years has been routinely used for the production of liquid explosives on a kilogram scale (Figure 3).

The plant has extensive safety features and is fully controlled and monitored remotely. Its modular design makes possible both the continuous synthesis as well as the subsequent down-

stream processing of energetic materials, for example different nitrate esters, which are used in new explosive and propellant formulations.

Despite small fluidic structures, microreactors are also used at the Institute for the production of microparticles and microcapsules. These are produced based on emulsions. Precise control over droplet size and subsequent crystallisation and polymerisation processes make it possible to produce monomodal spherical particles (Figure 4). This process can be used to shape and modify energetic materials and to encapsulate explosive particles.



Fig. 3: Microreactor-based plant for the continuous synthesis and downstream processing of liquid explosives at a kilogram scale

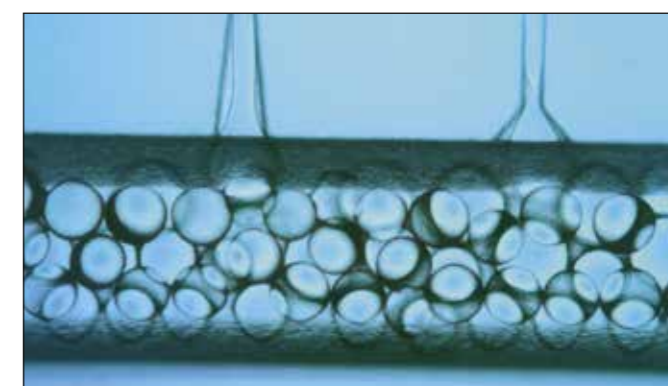


Fig. 4: High-throughput generation of emulsions, particles and microcapsules in a microchannel (microscope image)

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A terrain model for IR signature prediction using MIRA

MIRA (Model for InfraRed scene Analysis) is an infrared (IR) signature model for aircraft. It was developed at the Remote Sensing Technology Institute of the German Aerospace Centre as part of several Centre projects. These projects focussed on the design and assessment of combat aircraft. Last year, MIRA was extended to include a terrain model for the realistic representation of backgrounds.

The most important quantity in an assessment of IR signatures is the difference between the radiance emitted by an object and the radiance of the background. It is thus the contrast between target and background which permits or prevents the detection and tracking of a target. The structure of the background plays a decisive role. Detecting an object in front of a homogeneous background, be it a cold, clear sky or a uniform background with nearly constant temperatures, is a relatively simple task. If the background is randomly structured and exhibits largely varying temperatures, however, detection and tracking are much more difficult.

In order to achieve realistic predictions about detection, an IR signature model must not only determine the radiance of an aircraft. It also must take into account the influence of the background. It is of course also desirable to model a realistic background.

With respect to the Earth's surface, it is nowadays possible to obtain digital elevation models (DEM) and maps of the surface based on satellite data. It is also possible to include buildings



Fig. 1: Creation of a surface model for part of Hamburg (C) from a digital elevation model (A), building data (B) and a tree registry (not shown)



Fig. 2: Retrieval of material information from a satellite image. Color-coded material map for Fig. 1 (C); red: roof tiles, blue: water, light green: grass, dark green: trees, light grey: concrete, dark grey: streets

and even entire cities in the model. The following provides a brief overview of the necessary procedure on the basis of the city of Hamburg.

IR simulations require information about terrain, materials and temperature distribution. A surface model is therefore generated from a DEM, data on buildings, and a registry of trees (Figure 1). With this information, shadows and solar irradiation may be determined for different days and times. Materials that cover the ground are retrieved from images recorded by the WorldView-4 satellite (Figure 2).

A thermal simulation is then performed based on this data. Absorption of direct and diffuse solar radiation, thermal emission, and thermal conduction are taken into account. Absorption and emission depend on the orientation of the surfaces and the location of shadows. Figure 3 shows temperature profiles for June 15th (every 2 hours) in the air above roof panels and in the bricks below.

With this background model, the IR signature and contrast are determined. Calculations must consider the influence of the atmosphere, which attenuates radiation from the ground and from the aircraft to the sensor. The atmosphere also emits IR radiation. MIRA accounts for both of these effects by employing the MODTRAN atmospheric model.

Gases in an exhaust jet act in the same manner. Due to their higher temperatures, however, the effect is stronger. MIRA also takes this influence into consideration using a spectral band model that was developed especially for high temperatures. Figures 4 and 5 show two images of IR signatures of a wing-

only aircraft calculated by MIRA. The aircraft is a design produced by Diabolo, a Centre project. Surface temperatures of the aircraft and the composition of the exhaust were determined by the Institute of Propulsion Technology together with the Institute of Aerodynamics and Flow Technology. In the simulation, the plane flies at an altitude of 1 km above the town at a speed of Mach 0.5. The camera has a field of view of $3.6^\circ \times 3.6^\circ$ and is a distance of 1 km from the aircraft. It measures values in the spectral range of $3.3 \mu\text{m} - 5.0 \mu\text{m}$.

The contrasts of Figures 4 and 5 differ by a factor of nearly 2. At 04:00 UTC, the background is still cold and the radiant intensity contrast is 9.4 W/sr . At 11:00 UTC, the sun has heated the city. The contrast is now only 5.0 W/sr . Detection is thus more difficult.

This work allows us to make substantially more realistic assessments of IR signatures. MIRA, the IR signature model of the Centre, was thus significantly improved.

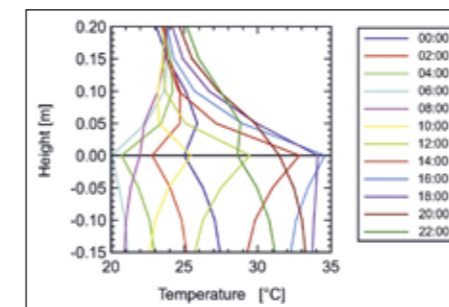


Fig. 3: Thermal simulation: Vertical temperature profiles on June 15th (every 2 hours). Roof tiles at height 0, air above, brick below

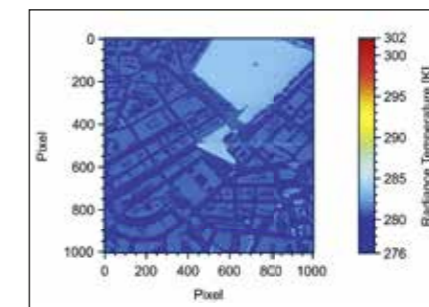


Fig. 4: Aircraft over the city of Hamburg, altitude 1 km, speed Mach 0.5, date and time October 5th, 04:00 UTC (centre of Hamburg, Binnenalster)

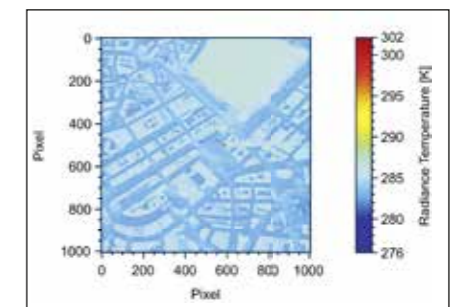


Fig. 5: Aircraft over the city of Hamburg, altitude 1 km, speed Mach 0.5, date and time October 5th, 11:00 UTC (centre of Hamburg, Binnenalster)

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Adaptive air inlet for a ramjet-propelled interceptor missile

Ramjet-propelled missiles are usually equipped with fixed propulsion components such as an air inlet. These offer maximum performance only under certain design conditions. An adaptive air inlet, however, can be adjusted to different flow conditions and can thus achieve high efficiency over a large range of conditions.

Airbreathing ramjet propulsion is a promising technology for future intercept missiles. This type of propulsion has a higher range than missiles with solid propellants, and the continuous operation of the propulsion system provides additional flexibility in case the point of intercept has to be adjusted. A critical component that influences the performance of the propulsion system is the air inlet. This component captures the incoming air for combustion and compresses it aerodynamically to the required pressure. However, conventional fixed air inlets operate at maximum efficiency only under certain conditions. Divergence from these conditions, for example on account of flight manoeuvres, leads to performance losses at the inlet and subsequently to decreased overall ramjet performance.

An adaptive air inlet, however, offers greater independence from changing flight and / or operational conditions. The geometry of the inlet can be adapted to current flow conditions in order to operate as close to maximum efficiency as possible as well as to ensure stable and robust operation.

As part of its missile technology activities, which are supported



Fig. 1: Adaptive axisymmetrical air inlet model with extended (top) and retracted (bottom) central body

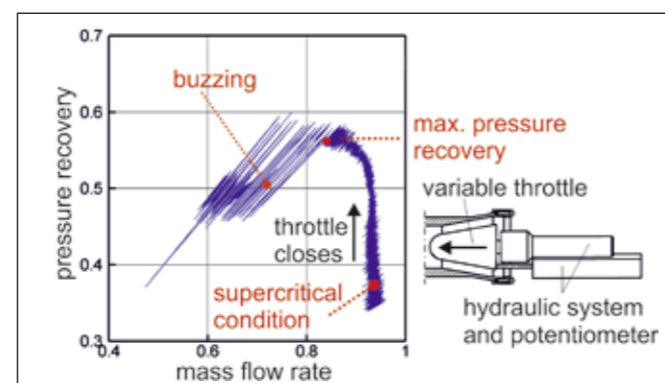


Fig. 2: Typical air inlet performance characteristic (throttle curve)

by funding from the German Ministry of Defence, the German Aerospace Centre is exploring the technical potential of such adaptive air inlets for ramjets. Currently, the focus is on a fully axisymmetric inlet for an airbreathing (generic) interceptor that operates at high supersonic up to hypersonic velocities. Figure 1 shows the wind tunnel model of an air inlet with a transversally movable central body which has been studied in the wind tunnels of the Department of Supersonic and Hypersonic Technologies. Performance characteristics of this inlet, also called throttle curves, were determined in a Mach range from Mach 2.5 to Mach 6 and at different angles of attack ($\alpha = 0^\circ$ and $\alpha = 3^\circ$). The back pressure from the combustion chamber is simulated by a hydraulic throttle downstream of the inlet. A typical performance characteristic representing pressure recovery of the inlet as a function of the mass flow ratio is shown in Figure 2.

Another important aspect of air inlet operation is its starting behaviour. This determines the transition Mach number, i. e. the Mach number at which the air inlet and thus the propulsion system becomes operational, and also the capability to restart, i. e. the capability to re-establish the inlet flow field after a breakdown of the flow (known as an unstart or blockage). Starting behaviour was analysed in the experiments by translating the central body axially in downstream direction until the internal contraction of the inlet increased to a level where it caused the inlet flow to unstart and a strong shock developed in front of the inlet. Then the central body was moved in upstream direction until the inlet flow was re-established, thereby determining the point of restart. Figure 3 shows the resulting maximum possible contraction ratios for Mach 2.5 to 5.3.

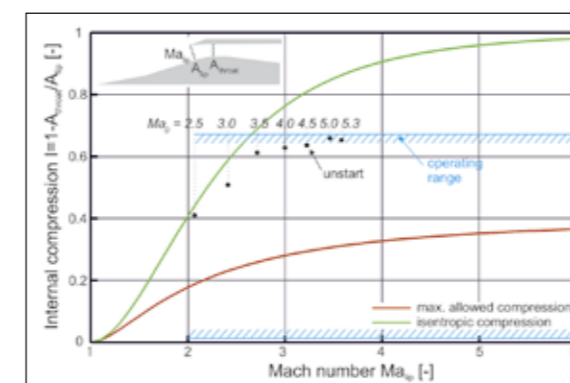


Fig. 3: Maximum contraction ratios

It was also found that, by moving the central body of the adaptive inlet, the occurrence of strong pressure oscillations, also known as inlet buzzing, could be alleviated (see the schlieren sequence of buzzing in Figure 4). Buzzing should be avoided because it involves high dynamic loads that can lead to structural failure.

Overall, the results of current studies, together with those from former studies on adaptive 2D inlets, provide information about the potential of adaptive inlets for several types of inlets, for example for semi-rotational symmetrical inlets. The results can also be used to increase the performance of ramjet-propelled interceptors as well as their mission flexibility.

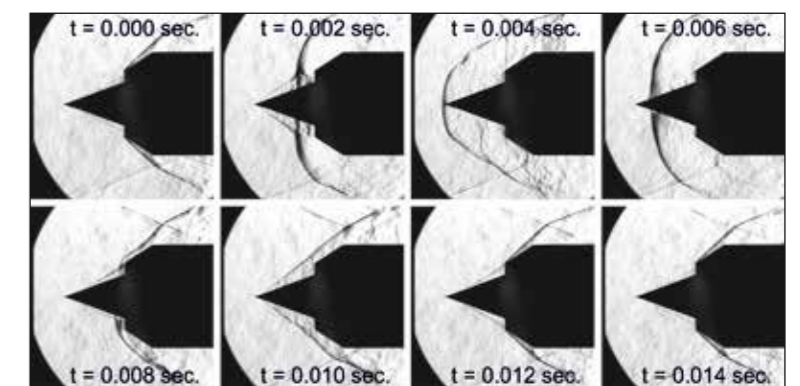


Fig. 4: Schlieren sequence of air inlet during buzzing

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Drone strikes on helicopter windshields

Drones are increasingly sighted near helicopters. Deliberate collisions of drones into helicopters pose an additional threat on operations. The objective of research at the German Aerospace Centre is to quantify the risk of drone strikes compared to bird strikes. Computer models are used to study both helicopter structures as well as impactors.

Research in this field is affected by certification specifications and commercial developments. Bird strike safety is an important impact requirement for medium and heavy helicopters in the airworthiness regulations EASA CS-29 and FAR 14 Part 29. Aircraft must withstand a 1 kg bird strike at maximum operational speed; uncritical damage is, however, allowed. Possible drone strike scenarios result from the fact that small drones are increasingly operated in the same airspace as helicopters and birds.

Parametric modelling of multicopters was used to assess the effects of a drone strike. The model was based on and validated by the most common quadcopter with 4 arms and rotors, including the battery (Figure 1) and motor (Figure 2). Similarly, bird models were created parametrically to account for different weights and shapes. Although the shapes are based on real birds, artificial bird shapes have not been standardised. Standardisation is an issue in the international working group SAE G-28, which was initiated by the German Aerospace Centre. The Centre is working on a reinforced artificial bird (RAB). The RAB can be adapted to all shapes usually used in industry

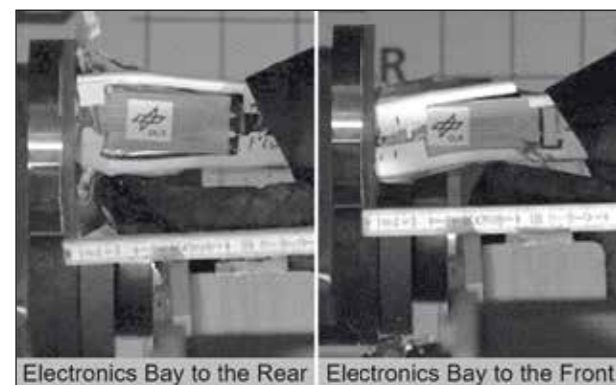


Fig. 1: Impact measurement of small drone battery at approximately 110 km/h with two orientations

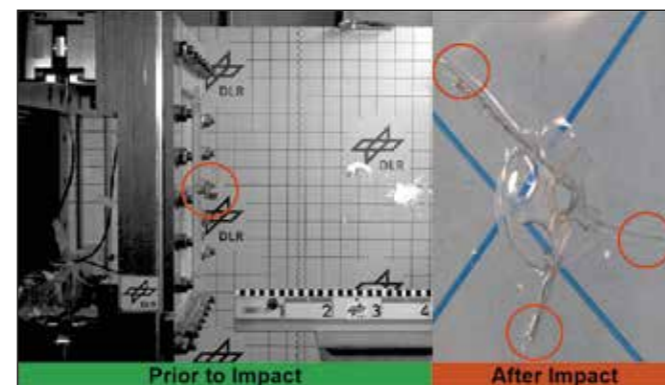


Fig. 2: Impact of small drone motor at approximately 580 km/h on polycarbonate windshield with 6 mm thickness and subsequent perforation and cracks

and research (Figure 3). This makes testing easier and provides more reproducible results compared to real birds.

In addition to the modelling and simulation of impactors, research is focussing on the analysis of realistic impact scenarios on structures. Efficient simulation approaches are needed in order to account for numerous load cases. Validation is based on component tests that are increasingly prepared and analysed by numerical simulation (Figure 4).

Research is based on mechanical characterisations that start at detail level and continue to components and full-scale. Energy dissipation of the flying structure and the foreign object is observed since both are responsible for damage. Despite similar weights, the material properties of drones and birds are obviously very different.

Research at the Centre is focussing on the windshield, the part of helicopters most frequently affected by bird strikes. Polycarbonate in particular is being studied as this material exhibits superior properties. Coatings are, however, required to achieve hardness and UV resistance. The first industrial application was for the fast RACER helicopter, for which the Centre developed a windshield demonstrator.

The demonstrator consists of an almost 10 mm thick windshield, coatings, adhesive bonding and a representative canopy frame. It acts as a validation unit for drone and bird strikes under similar impact conditions (Figure 5). The safety of pilots and passengers was analysed based on tests of the demonstrator with different impact scenarios.

Tests have shown that direct penetration through the windshield is not likely. More research is needed to determine whether drone strikes can possibly threaten helicopters currently in operation which have much thinner windshields. Not only the front glazing but also the adhesive joint and the canopy frame are affected and need to be studied.

Along with these quadcopter impact studies, the German Aerospace Centre is preparing modelling and simulation with fixed-wing drones. This is based on commercially successful small drones of EASA drone category C2 with up to 4 kg take-off weight.

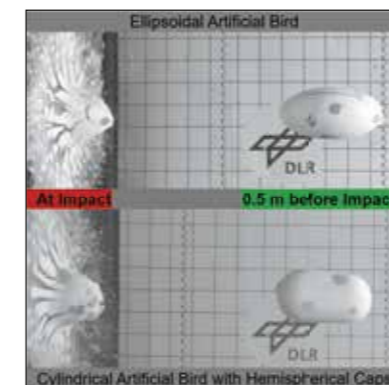


Fig. 3: Comparative impact measurement test with two artificial bird shapes, reinforced artificial bird (RAB) of the German Aerospace Agency with 1 kg at 410 km/h

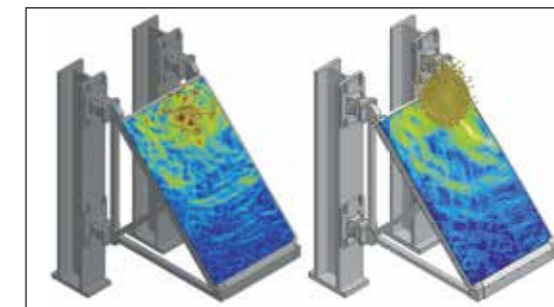


Fig. 4: Numerical simulation of drone strike (left) and bird strike (right) at 410 km/h on a windshield demonstrator of a helicopter canopy which is assembled on a test bench

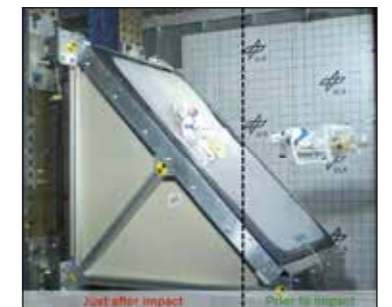


Fig. 5: Impact tests of quadcopter drone with 1 kg weight at approximately 410 km/h on a windshield demonstrator of a helicopter canopy

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Recognition of airplanes in space-borne radar remote sensing

Artificial intelligence (AI) already plays a major role in practical applications of remote sensing, at least in the electro-optical community. In the case of radar sensors, there are still some challenges to overcome through research. This article highlights promising studies for the traditional application of object recognition. These studies incorporate software tools by the German Aerospace Centre and Airbus combined with high-resolution TerraSAR-X radar imagery.

The availability of image data has been dramatically increasing along with numerous planned earth observation satellite missions. This mass of data must be rapidly exploited, which means that automation will become a high priority. In this regard, groundbreaking developments in AI in recent years are of utmost importance. Advances in the traditional field of object and pattern recognition can be mostly observed in the electro-optical sensor domain.

A direct transfer of these approaches to radar remote sensing is not promising. Additional challenges arise from the substantially lower amount of data and from specific characteristics of radar imaging. This includes particularly strong noise effects, disconnected signatures with point-like scatterers, and strong changes in its appearance as a result of slight transformations in the viewing angle. In contrast, a positive aspect is that radar sensing guarantees images independent of time and weather conditions and ensures constant illumination of a scene over long periods of time. This ensures ideal conditions for robust change detection. RADIAN software developed at DLR already provides operational tools for automatically detecting regions

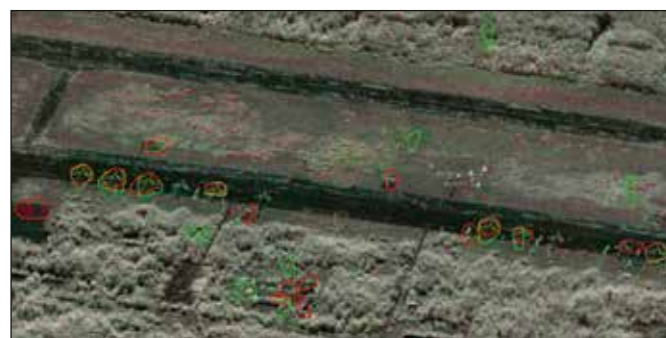


Fig. 1: Automatic detection of potential target objects with RADIAN. Processing of two TerraSAR-X images with segmented regions of change in red (appears) and green (disappears). Stationary airplanes (no change) are not detected. False alarms due to vegetation can be suppressed in most parts

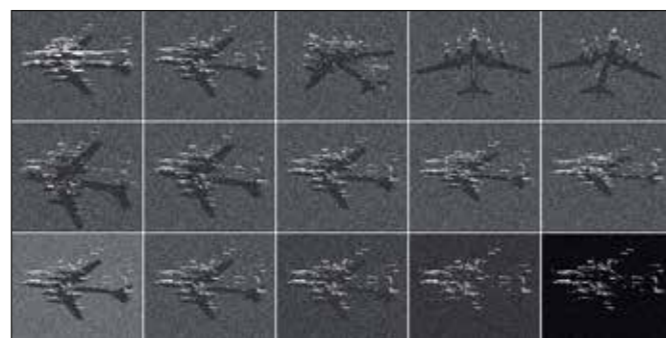


Fig. 2: Signatures simulated with SAREF for a certain type of airplane. Angle variations of orientation (top), angle variations of incidence (middle), intensity variations of background clutter (bottom)

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of change in a series of images (see Figure 1). Such information can be very beneficial for subsequent classification. The detection of potential target objects can narrow down the search area within the scene, which can significantly reduce the number of false alarms and boost computational efficiency.

The AI toolset CeMore Deep by Airbus extracts feature vectors by means of a pre-trained artificial neural network. Recognition is achieved by a support vector machine that is trained with radar signatures of the object type in question (in this case, manually recognised airplanes from TerraSAR-X data). Figure 3 illustrates the recognised airplanes from a distinctive test dataset. In an ongoing study, this classifier was compared with a counterpart that has been trained with synthetically generated signatures of the same airplane type. SAREF simulation software, which was developed at the German Aerospace Centre, was used for the necessary simulations. Figure 2 shows examples of synthetic signatures of the airplane type in question for varying imaging parameters. The substantial change in signatures depending on different observation angles can be seen. This variation calls for a large amount of finely sampled training data, which cannot be provided by real signatures. The missing gaps in a training dataset can be filled by smoothly simulating parameter ranges for incidence angle, local orientation, and background clutter. Figure 4 shows the airplanes recognised

using the classifier trained with simulated signatures. What is remarkable is that recognition is nearly the same, although the classifier never learned from a real airplane signature of this type.

These results show great promise for future studies. These will encompass studies of further airplane types and improvements in simulation. Their limits are mainly set by the quality of 3D model data but are also strongly dependent on unknown local conditions in the vicinity of the target object. A strong reduction in recognition rates has been observed for scenes where unknown objects were positioned near the airplane or where the texture of backgrounds varied greatly. This is a problem not only for simulation-based classifiers but also for training with real signatures. Fortunately, new ideas are already being implemented in pre-processing – in addition to the above change detection – that could significantly improve recognition rates.

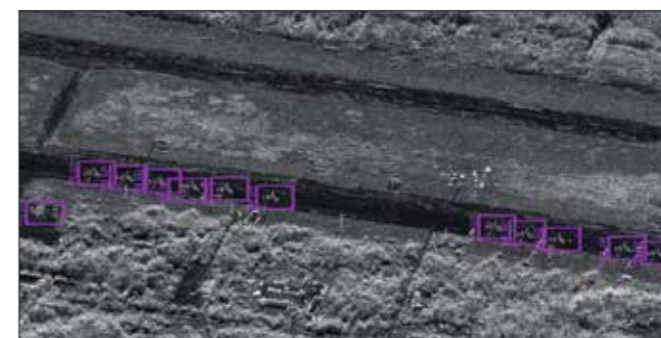


Fig. 3: Automatic recognition of airplanes with CeMore Deep. Classifier trained with real signatures (source: Airbus)

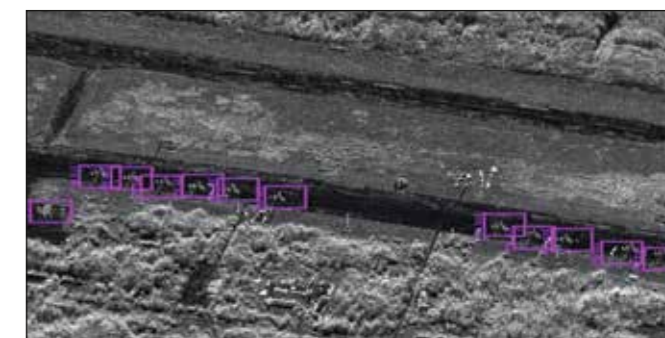


Fig. 4: Automatic recognition of airplanes with CeMore Deep. Classifier trained with synthetic signatures from SAREF. False negative samples for other types of airplanes, infrastructure and background clutter are trained from the same real training dataset as the classifier in Figure 3 (source: Airbus)

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Research on territorial air and missile defence

Hypersonic aerial vehicles will be game changers in future wars. Ballistic missiles are a constant threat, and new players are emerging. Area-denial weapons are leading to new developments such as armed drones and loitering munitions. Warfare in the aerial domain is changing. A joint project involving three institutes of the German Aerospace Centre is investigating sensor-related topics in aerial defence.

The Sensors for Aerial Defence joint project focuses on methods of detecting and tracking flying threats. This area of research involves many different tasks along with different strategies and solutions. Work in this project focusses on territorial defence against ballistic and hypersonic missiles. As a first step, specific aspects of hypersonic glide vehicles are being investigated.

In order to identify suitable methods for identification and tracking, the operation of a hypersonic glide vehicle was divided into phases. Suitable sensors and sensor platforms were investigated for every phase separately. Hypersonic glide vehicles are launched using ballistic missiles and engage their target in a manner similar to ballistic missile warheads. For this reason, methods for defending against ballistic missiles may prove useful for defence against hypersonic glide vehicles.

Launch detection is one of the oldest ballistic missile defence methods, but its information value is limited to an unspecific early warning. For ballistic missiles, observation of the boost phase burn-out is essential. Speed and direction at this point



Fig. 1: Generic hypersonic glide vehicle configuration used for modelling signatures

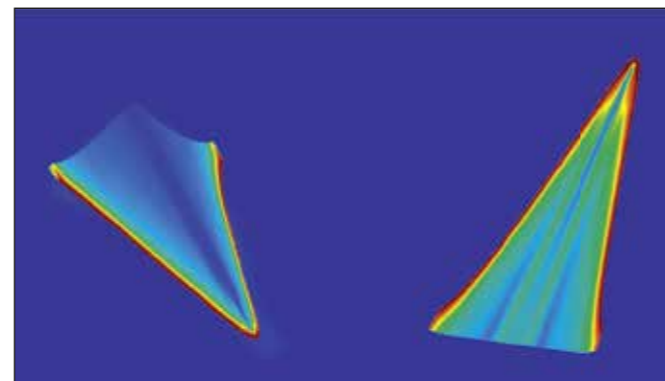


Fig. 2: Infrared signature of a hypersonic glide vehicle from different perspectives

determine the impact area. For hypersonic glide vehicles, this information is of little use on account of their manoeuvrability.

Detection and tracking therefore depends on the midcourse flight phase of such vehicles. This phase can prove difficult for ground-based sensors, as their field of view is limited by the horizon. Hypersonic vehicles also operate mostly inside the atmosphere and thereby can avoid detection by ground-based sensors much longer than ballistic missiles.

These limits of ground-based systems can be overcome by technologies such as over-the-horizon radar and by sensors aboard airborne or space-based platforms. While satellite platforms have been used for launch detection and boost phase tracking, midcourse tracking requires a different approach.

In order to understand the sensor requirements for the midcourse tracking of hypersonic glide vehicles, a different DLR research project studied and tested such vehicles in simulations. This made it possible to generate radar and infrared signatures of hypersonic glide vehicles in motion. With these signatures, sensors for midcourse tracking and interception can be developed.

Infrared sensors appear to be well suited to midcourse tracking. Vehicles travelling in the atmosphere at hypersonic speed will increase in temperature. Unlike plume signatures from missiles, they will emit heat over a broad spectral range. If observation against a sky or space background is possible, a high contrast between the signatures of target and background can be achieved.



Fig. 3: View of a simulated flight path from an airborne platform

An ideal observation position is not always possible for the interception of hypersonic threats. In addition, distance information from a single point of view may be necessary. For this reason, radar appears to be a more suitable technology for this task. Specific requirements for interceptor sensor heads and possible approaches are being explored in this joint project.

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Optical stare-and-chase technology for monitoring and cataloguing orbital objects

Highly sensitive wide-field-of-view camera systems can contribute to the initial detection of orbital objects as part of a ground station sensor network. Such systems can be operated autonomously at remote sites. Subsequent hand-over to a laser tracking station allows precise orbit determination of newly detected objects.

The large number of current satellite missions is leading to a significant increase in the spatial density of objects in Earth's orbit. This is related in particular to space debris objects in a low Earth orbit (LEO) at orbital altitudes around 800 km. As a consequence, existing space infrastructure is exposed to a growing risk of collisions. Monitoring and cataloguing of the orbital object population is primarily done by radar-based station networks, for example the US Space Surveillance Network. As a complement to radar-based sensors, optical sensors in a stare-and-chase configuration can contribute to the initial detection and monitoring of unknown orbital objects. A subsequent handover to a laser tracking station allows precise orbit determination and cataloguing.

A prototype sensor consisting of a highly sensitive CCD camera and a wide-angle lens operated in staring mode has been developed by the Institute of Technical Physics. As no motorised components are necessary, such a system can be cost effective and requires low maintenance. The system is available for field testing and is a dust-tight, jet-proof and internally temperature stabilised prototype. A 9 megapixel CCD camera is used as a



Fig. 1: Design housing (compliant with IP68) with a rotatable elevation axis



Fig. 2: Wide-angle camera system in weatherproof housing during field tests. Orbital objects like the International Space Station are detected as short streaks



Fig. 3: A stacked multi-exposure frame shows the recorded tracks of three different orbital objects passing simultaneously over the sensor. The stars in the frame are used for astrometric calibration

sensor. The lens has a focal length of 100 mm and a field of view of approximately 20°. Images are processed automatically based on C++ algorithms, and detected streaks are analysed in reference to the star background using astrometric calibration procedures. Data are saved in the standardised Tracking Data Message format.

The system can monitor and process several passing objects simultaneously without limitations. Operation is limited to twilight phases in which objects are lit by the sun while the system is in the dark with a clear view of the sky. During pre-evaluation campaigns performed under good visibility conditions, extremely high sensitivity for locating orbital objects was achieved. For objects with radar cross-sections between 1 m² and 2 m², the sensitivity for LEO objects approached 50 %. In other words, every second object in the publicly available catalogue which passed the field of view was detected. For objects with a radar cross-section larger than 2.25 m², sensitivity was nearly 100 %. Sensitivity and resolution can be further improved by synthetic tracking. In this method, successive short-exposure images are overlaid in order to improve the signal-to-noise ratio. Initial investigations have shown that the detection threshold of object size can be reduced by up to a factor of 10.

Work is currently being carried out on integrating the hand-over process into a satellite laser ranging station. Such stations are operated by the Institute of Technical Physics. This will allow orbital objects to be monitored and the three-dimensional trajectory to be determined within a few metres directly after object detection. A high level of procedural synergy is expected, particularly with regard to pre-instruction by radar systems

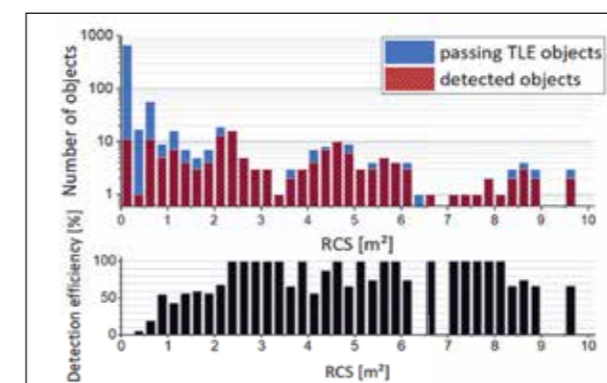


Fig. 4: Detection statistics of a 24-hour observation campaign as a function of the corresponding radar cross section (RCS). The upper graph shows the number of detected objects (red bars). The lower graph shows the corresponding detection efficiency between detected and passing objects

such as GESTRA (German Experimental Space Surveillance and Tracking Radar). Here, too, the accuracy of the trajectory data can be improved by follow-up measurements with a laser-optical ground station. This is especially important in the case of a critical conjunction between two orbital objects.

For the laser-optical tracking and ranging of orbital objects with dimensions down to 10 cm in size, the Institute of Technical Physics is currently building a high-end observatory for space surveillance and tracking. The telescope will have a primary mirror diameter of 1.75 m. The system is scheduled to be operational by the first quarter of 2021.



Fig. 5: Staring camera and 17-inch tracking telescope with mounted fibre-coupled laser transmitter

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Measuring the aerodynamic properties of finned projectiles in wind tunnels and in free flight

The German-French Research Institute of Saint-Louis (ISL) is investigating the flight behaviour of arrow-shaped projectiles such as those fired by main combat tanks and armoured personnel carriers. For this purpose, tests in supersonic wind tunnels as well as free-flight tests are being carried out at the ISL test site. The aim is to predict the trajectory and the accuracy of projectiles more precisely and to characterise factors that impair precision.

Arrow-shaped projectiles, as shown in Figure 1, are usually fired directly, i. e. they follow a flat trajectory. They can reach velocities of up to Mach 6. Since these projectiles are unguided, precise calculations of their trajectory are essential.

This requires aerodynamic coefficients, which can be measured or calculated using numerical flow simulation methods. Although modern calculation methods often provide sufficiently accurate results, they are not yet able to replace free-flight and wind-tunnel tests completely. This applies in particular to dynamic coefficients such as the pitch-damping coefficient.

To determine these parameters in free flight, a projectile is fired at an initial angle of attack of approximately 10° . A Doppler radar device records the velocity drop in the direction of firing, and high-speed cameras with synchronised rotating mirror optics track the projectile in flight. The drag coefficient can be calculated from the radar data. Video data indicates the angle of attack and changes in flight altitude along the flight path. Figure 2 shows the recorded oscillation of a projectile, which subsides over time. While the pitch-moment coefficient can



Fig. 1: Arrow-shaped projectiles

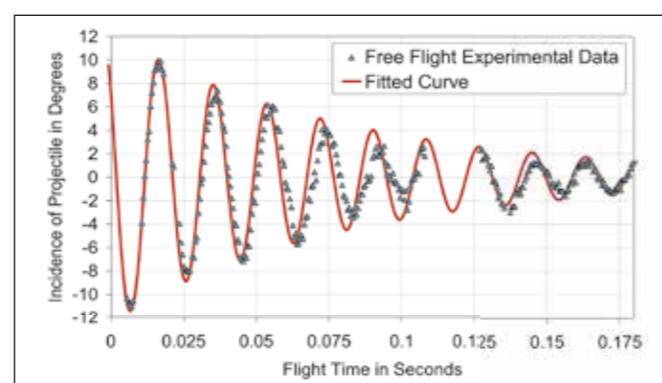


Fig. 2: Recorded trajectory and 2-DOF model fit

be derived from the oscillation frequency, the pitch-damping coefficient can be derived from the amplitude, which decreases more or less exponentially. For this purpose, an oscillation function with time-dependent frequency and damping is adapted to the data, which also takes into account the velocity drop during flight. Similarly, the lift coefficient can be calculated based on the change in flight altitude over time.

Tests in wind tunnels have two major advantages over tests in free flight. Firstly, the decay behaviour of projectile oscillation can be observed in a fixed frame of reference, which increases the quality of optical recordings. For this purpose, the projectile is suspended by a wire in the wind tunnel as shown in Figure 3. This allows it to oscillate freely around its centre of gravity.

The turbulent starting process of the wind tunnel induces an initial disturbance. The evaluation of the oscillation curve is then carried out in the same manner as in the free-flight test at constant flow velocity. Secondly, forces and moments acting on the projectile model can be measured using a force balance. For this purpose, the angle of attack of the projectile is varied during the test so that precise data on drag, lift and pitching moment can be determined including their dependence on the angle of attack. Attention must be paid to the effects of air flow on the necessary model mounting structure, which impact above all the drag coefficients since the pressure on the projectile base is altered by the mounting. As in a free-flight test, the drag coefficient can then be determined based on the difference between the base pressure measurements obtained with the force balance assembly and, alternatively, with a wire suspension.

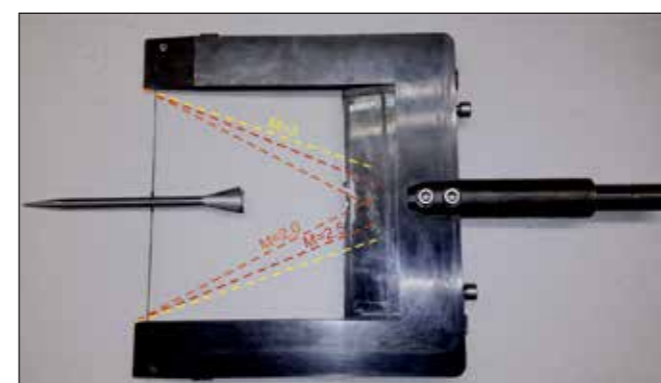


Fig. 3: Wire-suspended model for ISL trisonic wind tunnel

The combination of wind-tunnel measurements, free-flight tests, and numerical airflow simulations also carried out at ISL (see Figure 4) provides highly reliable aerodynamic data. These in turn serve as the basis for computing tools that are capable of precisely calculating projectile trajectories and that can characterise the effects of disruptive influences such as gun barrel vibrations and extreme environmental conditions. The identification and elimination of such disruptive influences leads to significant increases in accuracy.

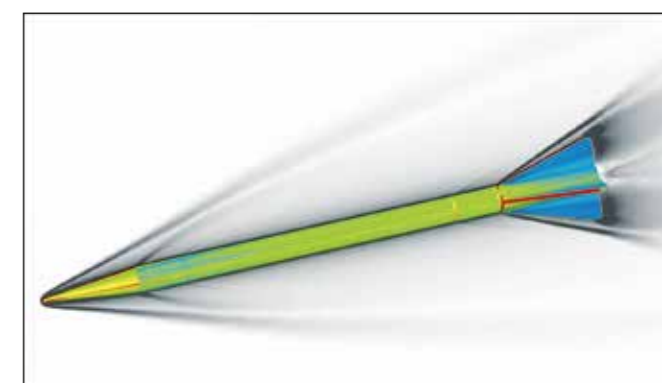


Fig. 4: Example of a numerical simulation

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Opto-pyrotechnic initiators

With improvements in laser emitters and continuous increases in the power available per volume unit and weight, new applications in which laser energy is used to initiate pyrotechnical reactions are being investigated. Based on this technology, the German-French Institute of Saint-Louis (ISL) has been developing opto-pyrotechnic initiators for space and defence applications. There are numerous advantages of such systems, especially in terms of safety.

ISL has been developing opto-pyrotechnic fusing systems since the 1990s, initially at the request of CNES, the French space agency. The objective was to replace the hot-wire devices on the future ARIANE space launcher with an alternative fusing system. The selected device designed by ISL is a two-stage opto-pyrotechnic detonator (OPD) that is based on a shock-to-detonation transition (SDT). In the first stage, laser energy triggers a rapid combustion of a secondary explosive which generates high-pressure gases that accelerate a small projectile at high velocity. In the second stage, this projectile impacts a compressed secondary explosive and triggers an SDT provided that the velocity and pressure are high enough.

The first designs used special optical components to maintain the tightness of the device and the focus of the laser beam on the pyrotechnical material in order to ensure high power densities. Additional requirements led to an optimisation of the opto-mechanical design without optical components but with direct contact between the optical fibre and the pyrotechnical material. While the first prototypes required expensive laser sources, current models use opto-pyrotechnical igniters with



Fig. 1: Opto-pyrotechnic detonator with its harness



Fig. 2: X-ray cineradiography pictures from the terminal flyer

off-the-shelf, inexpensive laser diodes with a few watts of power.

To ensure the reliability of the laser initiation step after extreme thermal cycling between -110 °C and $+110\text{ °C}$, a small layer of high-safety pyrotechnical composition is added for the space version of the opto-detonator in order to compensate for the thermal shrinkage and expansion of the various materials. For defence applications, which require fast functioning but will be used in a reduced temperature range, satisfactory results can be obtained with only secondary explosive mixed with an optical dopant that is necessary to absorb the laser radiation. Thanks to recent efforts to optimise the device design, the response time can now be finely controlled. For instance, at temperatures ranging from -50 °C to $+70\text{ °C}$, the average experimental functioning time for an initiation laser power of 25 W is 65 μs with a dispersion of plus or minus 5 μs . The compliance of the priming power has been validated both by measuring the characteristics of the OPD terminal flyer with X-ray cineradiography and by performing initiation tests on PBX boosters.

These positive results open up a whole new realm of possibilities for active protection systems. Particularly the narrow response time dispersion should authorise a precise synchronisation for triggering counter-measures, even against high-speed kinetic projectiles.

The ISL opto-pyro detonator offers many advantages in terms of risk reduction. The sole use of secondary explosives simplifies the safety of this firing system, which is compliant with REACH. It is immune to electric interference, insensitive to electrostatic

discharge and, thanks to its design, it can withstand thermal cook-off and fuel fire tests without detonating. Finally, it is compatible with multi-way initiating architecture and can be controlled over long distances due to the low power losses of optical fibres.

Current research is focussing on controlling the thermal initiation step. The main objective is to increase the quality and homogenisation of the initiation formulations based on secondary explosives by investigating new dispersion techniques. An expected benefit is the further reduction of the reaction time and its fluctuation.



Fig. 3: Fast cook-off (fuel fire test)

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Landmark-based methods for locating and navigating autonomous land vehicles in GNSS-denied regions

Unmanned ground vehicles (UGV) can be used to transport personnel and goods without increasing the number of drivers. Localisation and navigation are key tasks in their development. Especially in GNSS-denied regions, localisation techniques using sensors such as lidar (light detection and ranging) scanners are necessary for autonomous driving. This article provides an overview of the research on autonomous convoy operations.

Increasing the number of personnel and goods that can be transported with current transportation systems often means increasing the size of vehicles or the number of drivers. In some situations, both solutions are undesirable. UGVs can provide a solution in which one or more vehicles follow a lead vehicle (convoy operations). This problem is part of a study at the University of the Bundeswehr in Munich which is commissioned by the Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support. Two examples of UGVs can be seen in Figure 1. MuCar-3 and MuCar-4 are two research vehicles of the Institute for Autonomous Systems Technology.

Autonomous convoy operations have been developed and tested in recent years. Platooning in particular is an effective solution. With this technique, vehicles follow a lead vehicle using cameras or lidar sensors. Another more flexible option is the split convoy. With this technique, the lead vehicle gathers information which is used for its own localisation and the following vehicles' localisation and navigation regardless of the distance between the vehicles.



Fig. 1: MuCAR-3 and MuCAR-4 research vehicles from the Institute for Autonomous Systems Technology with roof-mounted lidar sensors

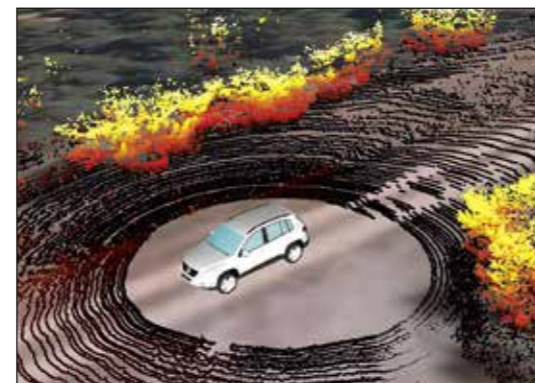


Fig. 2: Lidar point cloud. The colour of each point represents its height

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The lead vehicle continuously maps the environment and its own position. This technique is also called simultaneous localisation and mapping (SLAM). In our case, vertical landmarks such as bushes and trees are identified in lidar point clouds, as is shown in Figure 2. Clustering algorithms then extract object entities that can be seen in Figure 3. In the next step, the extracted entities are tracked with Kalman filters over time. If an object is seen in several iterations, it is considered to be a reliable landmark. Finally, we have several parameters that describe each landmark such as position, dimension and covariances.

Together with the movement of the vehicle, these landmarks are used to calculate the current position. All landmarks and positions are stored inside a graph, in which edges describe the association between positions and landmarks. This graph contains all information the following vehicle needs and can be transmitted to it.

Like the lead vehicle, the following vehicle extracts object entities from point clouds. Particle filtering solves the association problem: what landmark constellation of the received graph best fits currently recognised entities? This determines the current position of the following vehicle. Because the following vehicle follows the path of the lead vehicle, it can navigate



Fig. 3: Extracted entities. Each box represents a different object entity

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through unstructured environments. Figure 4 shows a scene from the viewpoint of the following vehicle.

To reduce the transfer rate, the amount of transmitted data is decreased intelligently. Positions and edges are only transmitted after a certain distance, which depends on the curvature driven or the steering-angle of the lead vehicle. This minimises discretisation errors in curves and reduces the transfer rate. Due to the small size of the graph and its further reduction, this approach facilitates transmission at low bandwidths.

The method of autonomous convoying in this article can be used in unstructured environments and situations where platooning fails or should not be used. Future research may include different sensors and environment information to make possible completely autonomous and reliable convoying.



Fig. 4: The lead vehicle continuously transmits landmarks (red cylinders) and its path (blue line)

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Centre for Crisis Early Warning pilot project

Germany's Federal Ministry of Defence initiated the Centre for Crisis Early Warning pilot project at the Bundeswehr University in Munich. The project seeks to develop innovative methods for improving crisis early warning systems. The Federal Foreign Office also participates in the project. Future participation is open to other federal ministries.

The Centre was founded in October 2020 and is currently working toward achieving initial operating capability. The Centre will help improve the capabilities and performance of the digital crisis early warning systems used by the Federal Ministry of Defence and the Federal Foreign Office. One of its research units will continuously review trends in machine learning and the interdisciplinary research area of crisis early warning. It will then apply these insights to relevant research questions in projects with the aim of conceptualising promising approaches and implementing them as proofs-of-concept. The other research unit will build upon this work and develop implementable proofs of concept. Another objective of the Centre is to participate in and promote international academic exchange in the field of crisis early warning.

The socio-economic conditions of a state (see Figure 1) and current political and social events (see Figure 2) can point to escalatory conflict dynamics in existing crises or to the risk of new conflicts. Risk assessments are generated by training models on a comprehensive database. These models seek to identify patterns that are associated with adverse political

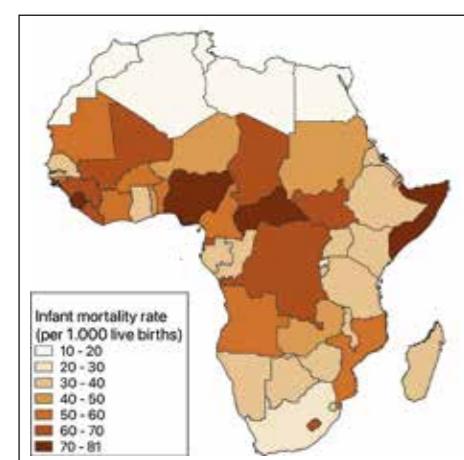


Fig. 1: Infant mortality rates are frequently used as a proxy indicator for the overall level of socio-economic development of a country (World Bank World Development Indicators)

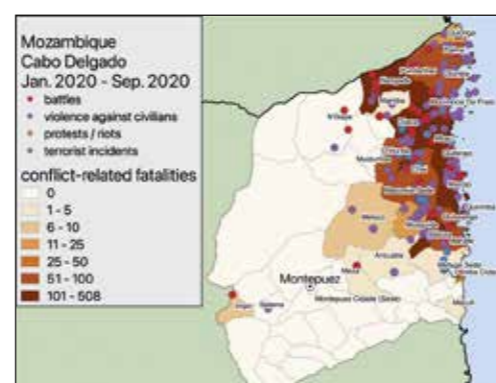


Fig. 2: Map showing conflict events in Cabo Delgado, Mozambique (Jan – Sep 2020) based on data from the Armed Conflict and Event Location Data (ACLED)*

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developments. In this way, crisis early warning systems support information acquisition and efficient analyses of conflict situations and thus facilitate better decision-making.

The primary objective of work at the Centre for Crisis Early Warning is the implementation of transparent and interpretable models that predict relevant phenomena such as conflict escalation and integrate new conceptual or methodological approaches.

An initial conceptual area of work is the improvement of crisis early warning models by focusing on actors instead of geographical regions. The focus on government, opposition, and rebel groups may result in more precise predictions about the intensification of (un)armed group behaviour, the spatial expansion of group activities, and the development of relations between actors. Figure 3 shows an example of an actor network extracted from such data.

A methodological focus of the Centre will be to evaluate the use of unstructured data in crisis early warning models. Unstructured data includes textual information such as news reports. The automatic processing, feature extraction and integration of news reports into analyses and predictive models facilitates a better link between input data and the resulting

model output and thus may improve model explainability. Test cases based on unstructured news data may also provide more general insights into the use of unstructured data sources as part of crisis early warning models, for example in the context of social media.

The research results of the Centre for Crisis Early Warning will be integrated into existing crisis early warning systems at the Federal Ministry of Defence and the Federal Foreign Office. The Centre will develop ideas for the integration of data and modelling results in existing dashboards, taking into account user ergonomics. An intuitive and visually appealing presentation of all model results is essential for effective decision-making support.

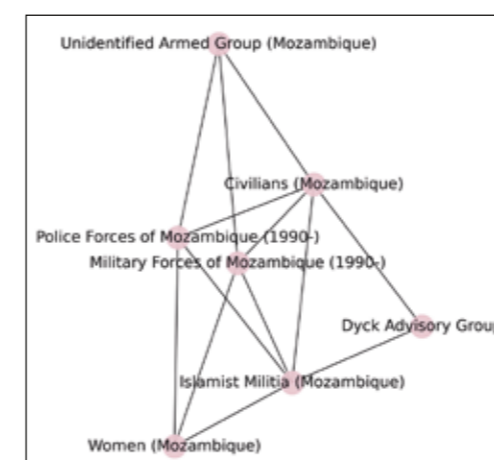


Fig. 3: Graph based on data from the Armed Conflict and Event Location Data (ACLED) project showing conflict relations between the seven most active actors in Mozambique (Jan – Sep 2020)*

* source: Raleigh C, et al. (2010) Introducing ACLED-Armed Conflict Location and Event Data. Journal of Peace Research 47(5), 651-660

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Investigating the potential of 3D printing of elastomeric components for military applications

Additive manufacturing (AM) processes are increasingly being used for military products. In addition to printing with construction materials, the printing of elastomer components is of particular interest when it comes to simplifying logistics. This topic is currently the subject of a research project at the Institute of Mechanics at the Bundeswehr University in Munich.

The printing of elastomers is the subject of a current research project at the Bundeswehr University in Munich in collaboration with the 3D Printing Centre of the Bundeswehr at the Bundeswehr Institute for Materials, Fuels and Lubricants. Elastomers play a significant role in many military systems. Elastomer components, such as seals in hydraulic systems, age during operation and therefore often need to be replaced. The wide range of elastomer materials, component designs, and complex aging processes (sometimes even during storage) lead to major challenges and costs for military logistics. AM could be used to produce replacement parts quickly and thus reduce costly warehousing.

Printed elastomers must have properties similar to conventionally manufactured elastomers. The goal of this project is to generate knowledge about the properties of printed elastomers and the applicability of component manufacturing processes. Examples of such elastomer components are seals, covers and rubber sleeves (Figure 1).



Fig. 1: High-strength silicone rubber component, 3D printing with material jetting (source: WIWeB)

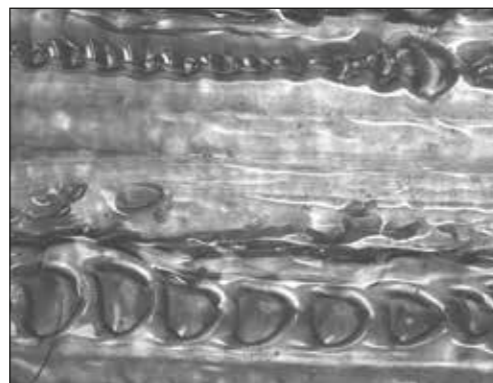


Fig. 2: Microscopic image of a thermoplastic polyurethane showing extrusion flaws from fused filament fabrication due to excessive moisture



Fig. 3: Flexibility of a cube printed with thermo-plastic polyurethane 82A by FFF (source: Vivianne Marie Bruère de Carvalho Paiva)

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Market research was conducted first to determine what current technologies were to be investigated and what their limitations were. At present, most printing processes do not allow the use of traditional non-vulcanised rubber. Instead, new materials are being developed for existing AM technologies which have rubber-like properties. This mainly involves printing processes using photopolymers – which are cured by UV light – or processes using thermoplastic elastomers (TPE) – a combination of a thermoplastic material with soft rubberlike components. A wide range of mechanical test methods are used to determine the properties of printed elastomer components.

Findings show that current 3D printing technologies for elastomer components still have considerable manufacturing limitations. Depending on both component design and requirements, different processes must be used. There are also significant deficits in material properties. Exposure to sunlight, for example, accelerates the curing of photopolymers and causes them to become brittle in a relatively short time. TPEs naturally melt when heated, are difficult to control during filament extrusion, and are sensitive to moisture, which can lead to bubbling and printing defects (Figure 2). It is therefore imperative to develop new materials with significantly more long-term stability and flexibility (Figures 3 to 6). Both properties are typical of traditional elastomers.

Although promising results are emerging, the demanding and complex material requirements for elastomers still limit the use of AM. The properties of conventional elastomers are not always available in printed elastomers. Mechanical properties are usually insufficient and the production of complex designs is not possible with all processes. Technological developments are becoming more and more dynamic. New processes, solutions and improvements are appearing almost daily.

Research on this subject must be continued, since only a sufficient understanding of the peculiarities and limitations of AM for elastomers will help make these printing processes usable for the Bundeswehr.



Fig. 4: Photopolymer TangoBlackPlus 70A from PolyJet after the tensile test (top) exhibiting high recovery to initial mould (bottom) (source: Vivianne Marie Bruère de Carvalho Paiva)



Fig. 5: Thermoplastic polyurethane estane 3D TPU M95-A from multijet fusion after tensile test (top) exhibiting medium recovery to initial shape (bottom) (source: Vivianne Marie Bruère de Carvalho Paiva)

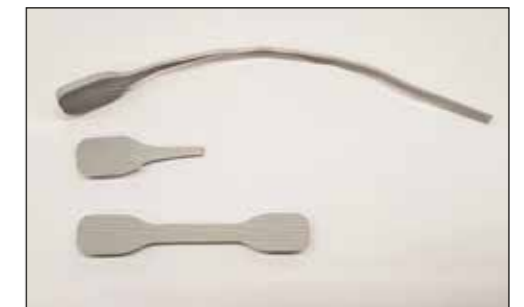


Fig. 6: Thermoplastic copolyester 86A (TPE) from FFF after the tensile test (top) exhibiting low recovery to initial shape (bottom) (source: Vivianne Marie Bruère de Carvalho Paiva)

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SOTM tests in the Bundeswehr

Mobile satellite communication with high data rates via SATCOM on the move (SOTM) terminals is essential for command capabilities in future Bundeswehr missions. The aim of the Digitalisation of Land-Based Operations programme is to realise this capability. The performance of such terminals was tested at the Bundeswehr University in Munich under realistic operating conditions.

SOTM terminals consist of an outdoor and an indoor unit. The outdoor unit is protected under a radome on a vehicle roof (Figures 1 to 3). It consists primarily of an antenna and a transmitter and receiver unit as well as components for antenna controlling and tracking. The indoor unit includes a modem, which, depending on the manufacturer's system configuration, can be supplemented with additional components for antenna tracking and control.

Numerous systems from various manufacturers are now available on the market. Different technologies are used depending on the terminal and the intended use. A central question in the development of new systems is always the trade-off between the highest possible data rate and excellent tracking performance on the one hand, and the lowest possible weight, low power consumption, and small size on the other. When it comes to antenna technology, a distinction must be made primarily between phased-array systems and traditional parabolic antennas. Phased-array antennas can have a flat structure. However, this technology is also mainly implemented as elevated panels in order to offer the largest



Fig. 1: SOTM terminal with traditional reflector antenna and with monopulse tracking approach from EM Solutions (source: ND SatCom, 2020)



Fig. 2: SOTM terminal with phased-array antenna technology from ADS (source: ND SatCom, 2020)



Fig. 3: Phased-array SOTM antenna from INSTER (source: ND SatCom, 2020)

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possible effective antenna surface even at low elevation angles. When it comes to antenna control and tracking, there are sometimes significant differences between the sensors and tracking algorithms used. A direct comparison of the performance of different terminals is therefore difficult and highly complex.

The reference and test facility for satellite communication of the Munich Centre for Space Communications at the Bundeswehr University in Munich is used to test and compare systems in a realistic environment. The ground component of the facility includes various antennas with a diameter of up to eight metres (Figure 4). All frequency bands commonly used in satellite communication are supported. The core of the facility is the extensive measuring equipment (Figure 5) for signal generation and recording with subsequent analysis and evaluation (Figure 6).

At the end of 2020, three other commercially available SOTM terminals were tested in cooperation with ND SatCom GmbH from Immenstaad on Lake Constance (Figures 1 to 3). The aim was to examine, among other things, the ability of the terminals to maintain a satellite connection while driving and to re-establish the connection as quickly as possible after shadowing by vegetation or buildings. The SKYWAN 5G-satellite modem

developed by ND SatCom, which is already in use in the German armed forces, was used.

The test results again show large differences in the tracking behaviour of the antennas, depending on how large and heavy the antennas are and what technology is used for tracking. Monopulse tracking methods have advantages over antennas with conical scan methods. In addition, the adjustment of the modem parameters to the antenna and the environment plays a decisive role in achieving theoretical data sheet values in practice. Precisely in this respect, the tests and discussions underline the necessity of a system integrator in order to deliver an overall system consisting of an antenna unit and modem which is optimised for the application and mission environment.



Fig. 4: Antennas of the Munich Centre for Space Communications at the Bundeswehr University in Munich (source: Thomas Benz, just imagine)



Fig. 5: Laboratory and measurement equipment of the Munich Centre for Space Communications (source: UniBw, 2019)

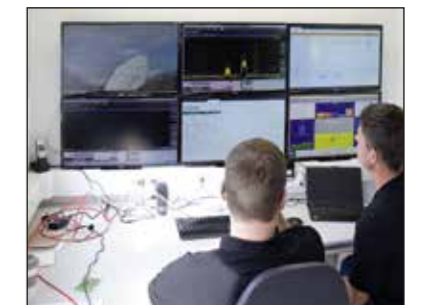


Fig. 6: Evaluation of measurement results (source: ND SatCom, 2020)

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Defence acquisition and supply management: Procurement research for the Bundeswehr

The Federal Ministry of Defence and the Bundeswehr University in Munich are cooperating in a new Defence Acquisition and Supply Management (DASM) research group in order to examine this field from an economic perspective. Cooperation is based on individual research projects carried out over the last ten years on, for example, the development of a procurement strategy and a market analysis of the defence sector.

The Bundeswehr awards contracts worth an estimated € 11 billion every year. It is thus the largest public purchasing organisation, buying a wide range of products from office supplies to complex weapon systems. Procurement represents an interface with the private sector. At the same time, the effectiveness and efficiency of industry essentially determines the operational capability of the armed forces. For the procurement organisation, it is therefore necessary to know procurement markets and to understand player behaviour.

This is all the more important as the Bundeswehr, like all public agencies, is required by budgetary and public procurement law to act economically. While the Bundeswehr does not operate commercially, it must nevertheless achieve the desired result with the least possible use of resources and thus in an economical way. To understand what effects procurement activities have on procurement markets and thus on industry, procurement research that is based on defence economics is necessary.

There is a long tradition of procurement research in business studies. The first explicitly procurement-related publication is



Fig. 1: Cost and performance management



Fig. 2: Defence acquisition and supply management research

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considered to be Kirkman’s “Purchasing and Materials Function”, a book published in 1887. The first course on purchasing and supply management was likely held in 1917/18 at Harvard University.

By contrast, there is little arms procurement research in Germany; procurement processes in the defence sector have so far been neglected by German researchers. In Anglo-Saxon countries, these issues are discussed relatively broadly under the term defence acquisition management. This approach considers the management of all dimensions, from requirements, development, production and operations to the disposal of a (weapon) system (Figure 1).

Against this background, the Federal Ministry of Defence has decided to pool research into defence procurement in a Defence Acquisition and Supply Management (DASM) research group and to provide appropriate personnel and material. This research group is based in the Procurement Working Group of the Bundeswehr University in Munich (Figures 2 and 3) and can thus benefit from contact with other research groups on public and industrial procurement (i. e. a junior professorship endowed by Audi AG and the Stifterverband für die Deutsche Wissenschaft).



Fig. 3: Bundeswehr University in Munich

The DASM research group was established at the beginning of the 2020/2021 academic year, but it is based on research that has been carried out at the Bundeswehr University in Munich. This includes in particular performance-based logistics (PBL), which is investigating new contractual relationships with suppliers. The focus is on linking a supplier’s remuneration to the desired performance result (e.g. the availability of a weapon system in percent). This avoids the false incentives of pure cost reimbursement contracts. Initial empirical findings have shown that PBL incentive systems can actually lead to higher availability (Figure 4).

The second major area of research is life cycle cost management (LCCM), which examines the total costs of the acquisition and use of a weapon system. For this purpose, a survey was carried out in the security and defence technology industry on the use of instruments that generate early estimates of total costs.

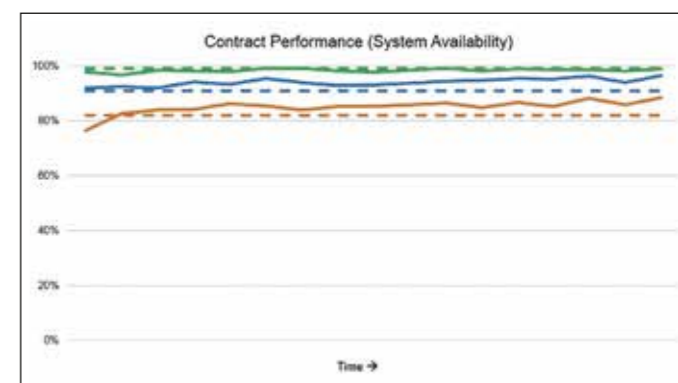


Fig. 4: Evaluation of system availability

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Promoting health effectively and efficiently

Effective occupational health management must reach out to employees and must offer suitable programmes, especially when it comes to mental health. In two projects, we analysed what factors promote and hamper participation in occupational health management (OHM) programmes and how stress management can be improved through appropriate strength and resilience training.

Participation and non-participation in occupational health management – Causes and countermeasures

With regard to perceived stress in the Bundeswehr, our results show that 35 % of a total of 1142 employees and 46 % of a total of 469 executives rate psychological stress and strain as “high” to “very high”. Over 71 % say they have a great or very great need for OHM programmes.

Among the employees with great and very great need for OHM measures, at least 71 % are already participating in such programmes. There are, however, 29 % with a great or very great need who have not been reached yet. Among those with little or no need, 19 % are taking part. We have identified the most important reasons for participation: health benefits of OHM (maintaining or improving health / fitness despite current problems), favourable organisational context (savings in terms of time, distance and costs; attractive programmes), positive word-of-mouth recommendations, and encouragement and active support from colleagues and leaders. Organisational, leadership, social and individual factors thus substantially



Fig. 1: Participants in the strength and resilience training programme learn about different resources

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contribute to the intention to participate and to actual participation. Important factors that hinder participation are unattractive programmes (for example only physical exercise), a fear of stigmatisation, a lack of support from leaders and colleagues, and unsatisfactory infrastructure.

Tailored stress prevention and resilience promotion in the OHM rollout of the Bundeswehr

The ongoing high prevalence of psychological stress at work has attracted attention inside and outside the Federal Ministry of Defence and the Bundeswehr. At the same time, OHM measures at different agencies of the Bundeswehr have primarily focused on physical activity and thus physical health. Specific and tailored measures to promote mental health are largely missing. Our project is making an important contribution to closing this mental health gap.

Evaluation results of our strength and resilience training for stress prevention (SRT; <https://staerken-ressourcen-training.jimdofree.com>, see Figures 1 and 2) show a significant improvement for SRT participants in terms of subjective criteria (mindfulness, self-care, positive emotions, serenity, resilience, stress and discomfort reduction) compared with an inactive control

group. A comparison with an active control group (progressive muscle relaxation) showed the superiority of the SRT in terms of self-care, mindfulness, and the reduction of discomfort and fatigue. Furthermore, and over time, SRT participants showed a greater increase in heart rate variability than PMR participants and the inactive control group.

In addition, we have developed, successfully implemented, and positively evaluated a programme for training peers to be SRT trainers. SRT was also successfully adapted to the military setting.



Fig. 2: SRT participants practice a mindfulness exercise (body scan)

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Command and control using IT

A shared information space in combination with distributed NEO-capable information management (NEO: Network Enabled Operations) provides both knowledge workers and military actors with an advantage and effects superiority. The concept of “command and control using IT” helps reorganise military “palaces of leadership” into agile developing “communities of interest” that can be adapted on an ad-hoc basis.

In the civilian sector, Industry 4.0 is currently fostering innovation, and the Internet of Things reveals a facet of Weiser’s vision of “ubiquitous computing”. In the military, this development is known as “network enabled operations”. “Ubiquitous computing” makes it clear that the path to success is not only through technology and applications. The integration of users with their knowledge, their potential for sensemaking, and their creativity is needed to ensure an advantage.

R&T studies have used an information network defined at the Bundeswehr University in Munich which dynamically connects humans and technology through information (H - I - T). In its semantic order, this information hub realises Schmidt and Bannon’s idea of the “shared information space” (SIS). The interconnection derived from NEO implements simultaneously content and modelling as an enterprise architecture (upper layers) in the information networks. Using the new information management cycle, users organise their command and control information and collaboration in a self-synchronising manner in pursuit of a common goal (command intent) to achieve agility and an advantage (Figure 1). Tried and tested procedures includ-

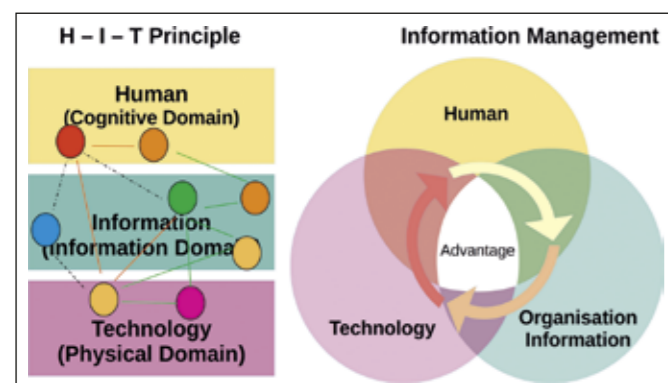


Fig. 1: Information management interconnects humans and technology via information (H - I - T) (source: Gerhard Schwarz)

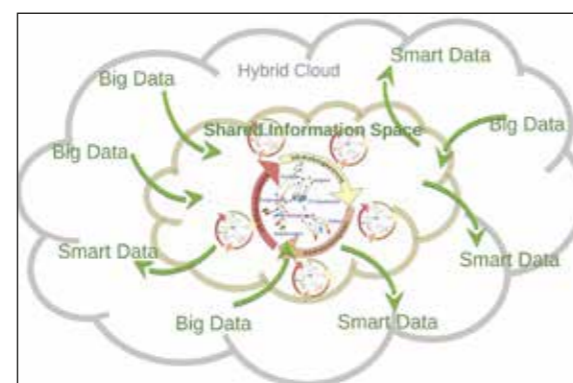


Fig. 2: NEO-capable information management in the shared information space cloud (source: Gerhard Schwarz)

ing modern technology stacks (Web-Oriented Architecture, microservices, etc.) are not replaced but instead are enclosed by the information networks and newly connected in a flexible way. Information management controls the exploitation of data at the technical level (data management) and connects command and control information through information networks with applications, which are further developed in an agile and dynamic way for the user with current “low-coding platforms”. The parallels to enterprise architectures allow for a smooth integration into existing IT governance (Figure 2).

Although the generic information management cycle is based on military command and control and has been reviewed by a prototype called “WhatsBw”, it is also suited for generally usable “mutual information” and sensemaking.

With these prototypes from R&T studies, it was possible to demonstrate that the information management cycle is suitable for military applications and for routine tasks such as messaging (Figure 3). The main advantage is the reusability of information in the work process and a parallel build-up of a knowledge base. This economical use of information, which is not only relevant to military command and control on operations, may also be applied to the development of armaments projects, planning and post-deployment measures, and in fields of cognitive activities. The Joint Support and Enabling Service has launched an initial study called “Command and Control Using IT” to combine military principles of command and control (mission command) with information technology through this collaborative approach to information management (Figure 4).

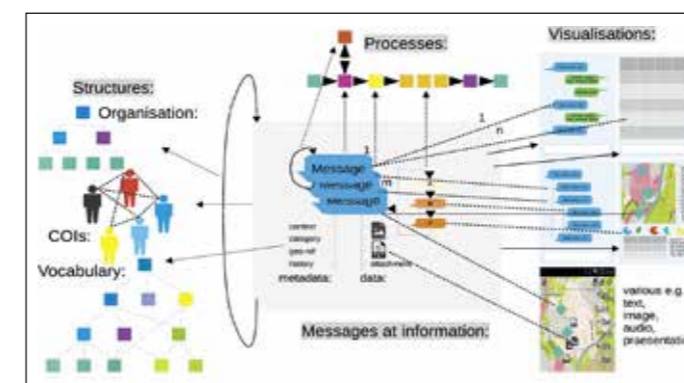


Fig. 3: WhatsBw messenger system sketch based on information networks (source: Gerhard Schwarz)

The focus of attention is on finding an acceptable compromise between increasingly faster development and response capability and clearly structured, elaborate, resilient and sustainable IT architecture. Using the Bundeswehr “method of architectures” as an example, the gap between modelling of the target state and implementation is particularly striking, as modelling and implementation may take years, which means the results are not (or no longer) convincing for users.

The information management cycle allows two main principles to be combined: the first is an agile build-up of an initial capability with dynamic use, agile updating and reuse of tried and tested elements of the target capability, and the second is an organisational structure that is constantly adapted to requirements in accordance with the community of interest principle. An early finding that was made in NATO’s Net Force study is that this is suitable for organising both highly agile command and control processes and permanent and optimised work processes. Both can also be supported by an SIS as a hub.

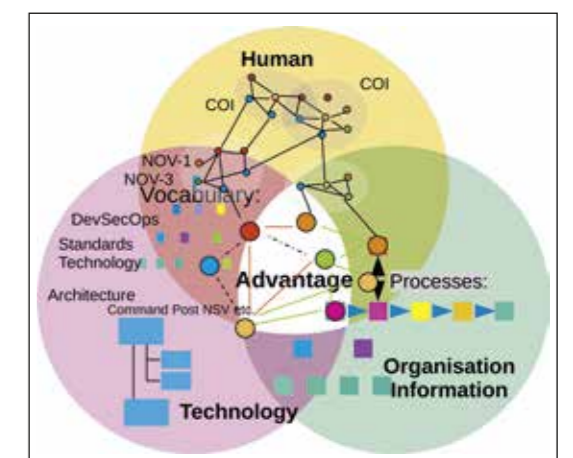


Fig. 4: Command and Control Using IT concept (source: Bundeswehr)

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Analysis of the recyclability of thermoplastics for use in additive manufacturing in the maritime sector

Additive manufacturing is increasingly being integrated into the maritime sector. Ships present a special environment due to their deployed naval location. Resources should be optimally used due to the limited storage capacity on board. The recycling of thermoplastic waste offers such an optimisation opportunity so that resources can be re-used on board.

The relevance of additive manufacturing using thermoplastics is continuously increasing in the maritime sector. Applications for the rapid production of spare parts on board are currently still at the research stage.

The pioneer in this area is the military maritime sector. Nations such as the United States and the Netherlands have already integrated additive manufacturing possibilities on board in the form of fused filament fabrication (FFF) printers. Currently, the material needed for FFF printers is stored until it can be used. When the demand for additive manufacturing on board increases in the future, the demand for materials will also increase. To meet this demand in an almost self-sufficient manner, the recycling of thermoplastics can make an important contribution (Figure 1). The results of filament recycling on a non-industrial scale do not currently meet the quality standards that are necessary for use and possible applications. At the same time, many thermoplastics are used on board in other forms, such as plastic bottles, which are then disposed of as waste after use. According to a German environmental aid organisation, an average of 200 bottles are produced per person per year, and such bottles

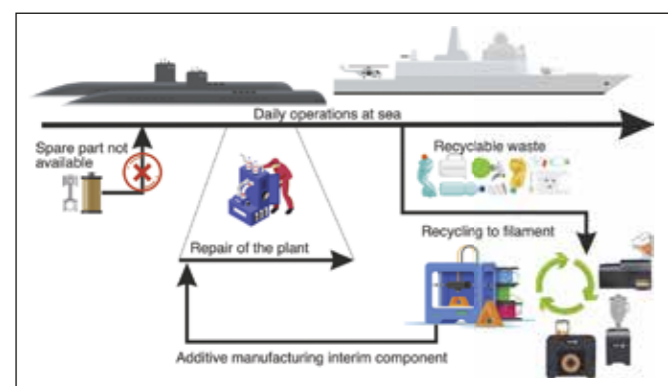


Fig. 1: Diagram of a possible application for 3D printing on board. The raw material for the printer is obtained by recycling thermoplastic waste on board



Fig. 2: Desktop filament production line with dryer (left) and extruder with integrated spooling system (right)

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also represent the majority of thermoplastic waste on board German naval vessels. In a cooperation project between the Manufacturing Technology Laboratory at Helmut Schmidt University / Bundeswehr University Hamburg and the German Navy, these unused resources are to be reprocessed in the laboratory into usable filament for FFF printing.

Initial experiments and studies of the recycling of misprints and waste products (Figures 2 to 4) are promising and offer potential for on-board use. Planned experiments with polymers that were not originally produced for 3D printing now represent the next logical step. Work on material recycling complements the plan to introduce additive manufacturing as a group of novel manufacturing processes for use in the Bundeswehr. Since additive manufacturing processes are able to produce individual items and small batch sizes economically, the aim is to use them to improve the supply of spare parts as part of obsolescence management in the Bundeswehr.

In addition to the CD&E project “3D Printing in the Bundeswehr”, which is dealing with the integration of additive manufacturing into existing Bundeswehr processes and procedures, the AddiMuK study project, which is supported by the Bundeswehr Research Institute for Materials, Fuels and Lubricants and carried out at Helmut Schmidt University, is primarily

examining technological and economic aspects of additive spare parts manufacturing using techniques and new methods of reverse engineering. The necessity of providing a process-specific starting material in a suitable form leads to a thematic intersection with synergy potential between recycling and decentralised additive spare parts manufacturing according to acute and specific needs. This makes it possible to investigate a special case of decentralised additive manufacturing, which could be highly relevant both for ships and boats of the Bundeswehr and in the future increasingly for the civilian maritime sector.



Fig. 3: Final process step of filament production extrusion of recycled material and subsequent spooling

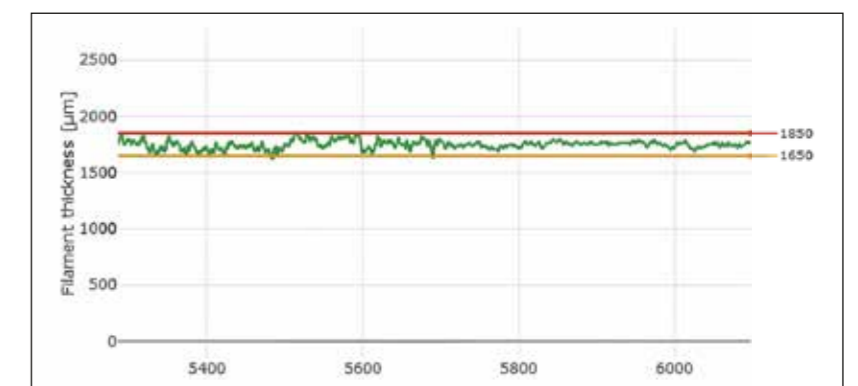


Fig. 4: Diagram of the filament diameter over the process time with upper and lower limit values for the production of 1.75mm PLA filament

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3D spatial audio for improving hearing protection devices of soldiers

Due to high noise levels on the battlefield, hearing protection devices (HPDs) are essential for soldiers and successful missions. Wearing HPDs can, however, reduce the situational awareness of soldiers. 3D spatial audio can be used to turn HPDs into transparent-sounding systems and to enhance audio communication by including spatial information in the transmitted audio signals.

Humans are able to localise sound sources based on the way sound reaches their eardrums via their anatomy, for example the outer ear, the head and the torso. Horizontal localisation is determined mainly by interaural time and level differences. Monaural spectral cues provide information about vertical localisation. All these cues are summarised in the direction-dependent, head-related transfer functions (HRTFs) between an external sound source and the eardrum. Due to natural differences in human anatomy, these HRTFs are highly individual.

Although stereo signals allow a sound source to be shifted along the interaural axis between the ears, neither vertical localisation nor externalisation is achieved (Figure 1). In comparison, binaural rendering through headphones restores three-dimensional localisation capability by recording or synthesising the two signals that would enter the human eardrum during natural listening. Although binaural recordings are easy to implement, reproduction is limited to the recorded sound scenes. In contrast, with binaural synthesis virtual sound sources can be positioned anywhere in 3D space by filtering a monaural audio signal with

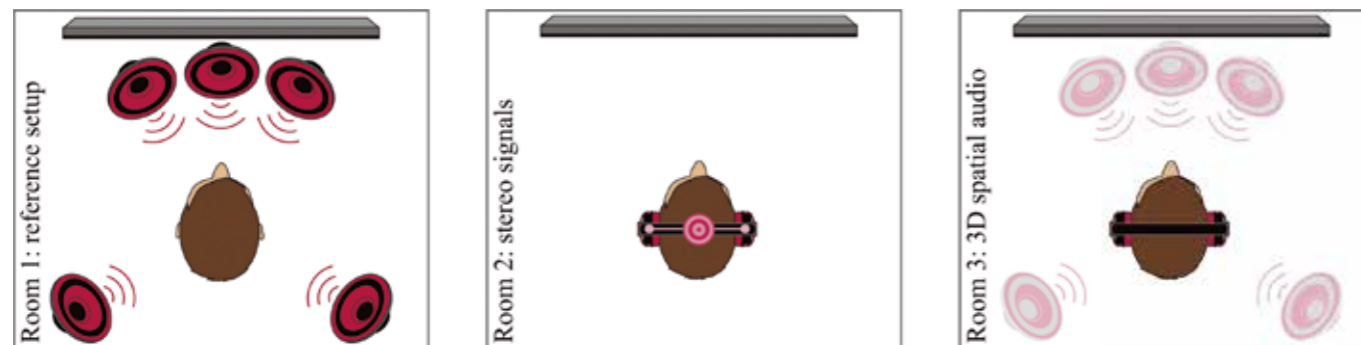


Fig. 1: Use of 3D spatial audio for a setup with five loudspeakers. Room 1 is the reference setup with five real loudspeakers. The loudspeakers are replaced by headphones in rooms 2 and 3. Stereo signals in the headphones in room 2 only allow shifts of the virtual sound source on the interaural axis between the ears. 3D spatial audio in room 3 allows the listener to sense externalised virtual sound sources in the direction of the real loudspeakers in room 1

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the corresponding HRTF pair. In this way, new sound scenes can be generated that make possible horizontal and vertical localisation as well as the externalisation of virtual sound sources. For soldiers, binaural synthesis can be used to enhance both hearing protection and audio communication.

High noise levels and shock waves on the battlefield pose a serious risk to the hearing of soldiers. Hearing protection is thus essential. Wearing HPDs, however, reduces localisation performance by altering localisation cues. Binaural synthesis can be used to restore sound signals and fulfil original cues. It therefore maintains the directional information of the external sound source. This results in a transparent-sounding HPD.

Binaural synthesis can also be used to enhance audio communication by including spatial information in the transmitted audio signal. In this way, the listener receives the message and the position of the speaker at the same time (Figure 2). The same technique can be used to enrich alerts with the transmission of the position of a threat. In multisource scenarios, the listener perceives individually spatialized sound sources rather than an indistinguishable mixture of all sounds. In this way, soldiers are able to focus and extract the most important information by listening in the corresponding direction. Binaural synthesis thus helps to improve speech intelligibility, resulting in a better

understanding of orders, faster reaction times, and an improved awareness of threats.

Previous research has shown that binaural synthesis based on the use of non-individual HRTFs is associated with increased directional errors, a higher front / back confusion rate, and in-head localisation. The cooperation project involving HSU and ISL focusses on new HPD designs as well as on measuring, simulating, and approximating individual HRTFs. Both approaches aim at improving binaural synthesis in terms of localisation accuracy and at ensuring the viability of light-weight and low-power systems in order to satisfy the specific requirements of HPDs for soldiers.

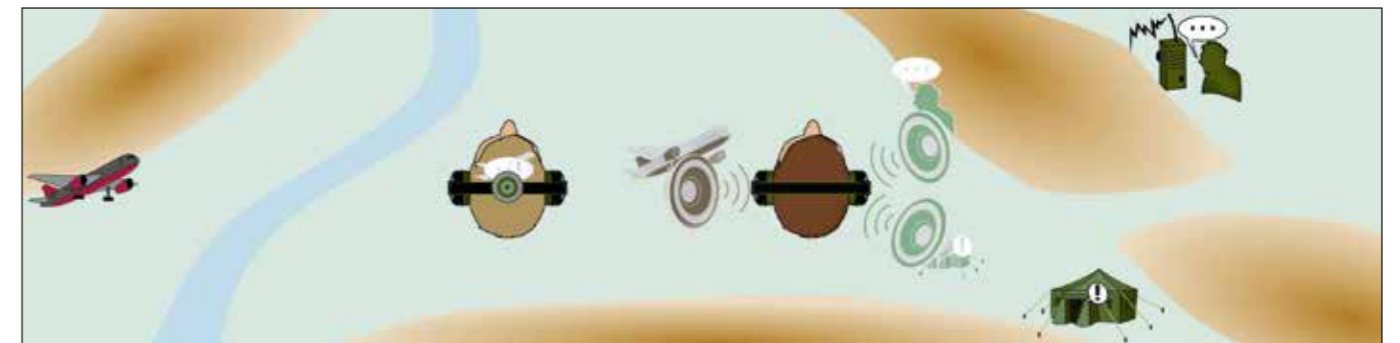


Fig. 2: Battlefield scenario with multiple simultaneous sound sources, e.g. a message from another soldier located at the front and to the right, a new order from the base camp located in the rear and to the right, and an alert about an enemy airplane on the left. The left soldier has an indistinguishable mixture of audio signals due to the simultaneous playback of all monaural audio signals. The right soldier is able to separate the different sound sources due to the spatial information inside the transmitted binaural signals.

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Use of additive manufacturing to produce surrogates for the analysis of non-lethal weapons

Validated and scientifically substantiated findings on the effects of non-lethal weapons (NLW) on the human body are limited. Such findings are essential, however, if we are to ensure that no serious or fatal injuries occur when NLW are used. A method must therefore be developed to predict the effects of kinetic projectiles on humans.

Agencies of the Bundeswehr lack testing and validation procedures to ensure that NLW meet complex and varied requirements. These can involve the use of bone and organ surrogates that mimic the shape and physical properties of tissue and bone.

The data and knowledge resulting from the testing and validation procedures can also be incorporated into modern simulation methods, which may reduce the number and scope of physical tests in the future. Procurement and manufacturing of surrogates that meet the necessary requirements are currently difficult.

Due to this lack of reliable surrogates, the Technical Centre for Protective and Special Technologies, Branch 320 and the Laboratory for Manufacturing Engineering at Helmut Schmidt University / Bundeswehr University Hamburg are working on the substitution of tissue and bone by surrogates. They have identified additive manufacturing as a core technology, as it can reproduce the complex structures of human anatomy.

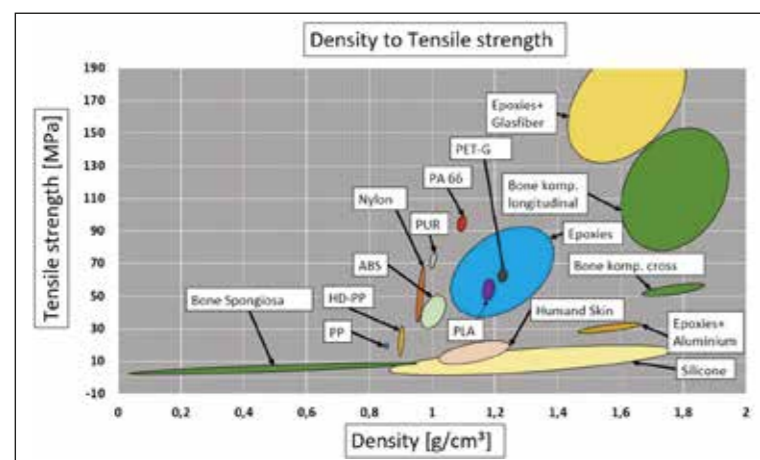


Fig. 1: Density and tensile strength of possible surrogate materials

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It is assumed, however, that a combination of processes will have to be used in the manufacturing process.

The aim of their work is therefore first to develop and prototype a process chain based on an analysis of current technology and an internal workshop. Bone and organ surrogates will then be manufactured in accordance with the identified requirements. A method will be developed for evaluating existing technologies for the production of surrogates (Figures 1 and 2).

With the help of selected technologies and materials, test coupons and bodies for the different requirements as well as different sizes and complexities are to be manufactured.

In December 2020, a four-day workshop on this topic was held by the above institutions, during which the core requirements and possible technologies for surrogate production were developed. We would like to thank the participating agencies and institutes that made a significant contribution to the success of this workshop:

- German-French Research Institute of Saint-Louis
- Fraunhofer Institute for High-Speed Dynamics, Ernst Mach Institute
- Research Institute for Materials, Fuels and Lubricants, Branch 240, in Erding
- University Medical Centre Leipzig, Institute of Forensic Medicine
- University Medical Centre Hamburg-Eppendorf, Institute of Forensic Medicine
- Technical Centre for Weapons and Ammunition 91, Branch 450
- Ludwig Maximilian University, Institute of Forensic Medicine
- Bundeswehr University Munich, Professorship for Weapons and Ammunition Technology

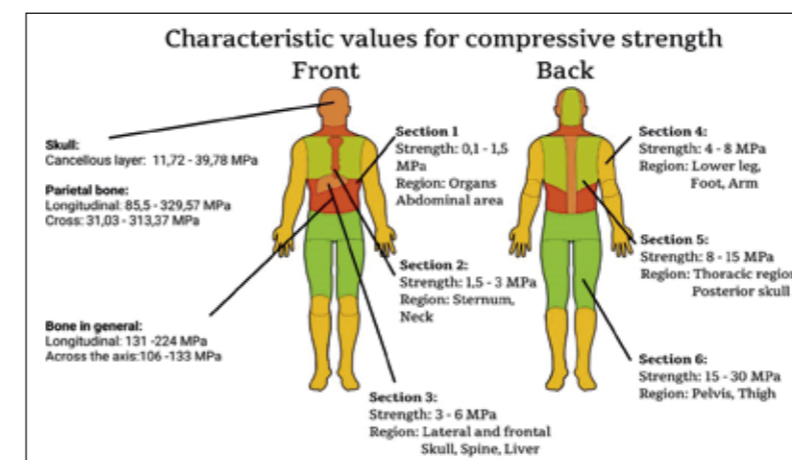


Fig. 2: Compressive strength of human bone and tissue

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Real-time detection, localisation and volume estimation of deflagrations in military vehicles

The computation time and the risk of false alarms of an image-processing-based deflagration detection system have been significantly reduced by adding infrared sensors to the system as well as by porting the algorithm to a field-programmable gate array. Novel algorithms have also improved the robustness of localisation and volume estimation.

Deflagrations in military vehicles pose a serious threat to crews (Figure 1). For this reason, crew compartments of armoured vehicles in the Bundeswehr are equipped with fire suppression systems that detect and suppress deflagrations even in early stages.

An alternative to Halon, which is already banned, and other ozone-depleting suppression agents is water mist, which does not pose a risk to human health. Its full suppression potential can only be achieved, however, when it is applied directly at the deflagration. For this reason, systems must not only detect a deflagration at an early stage, they must also locate it and estimate its volume.

Current detection systems are based on infrared sensors. They are able to detect deflagrations fast enough (< 15 ms) but are not able to provide further information about position, size or rate of expansion. They are thus not compatible with water-mist systems.

In two preceding projects, an algorithm was developed for the detection of deflagrations in images taken by multiple high-



Fig. 1: Development of an artificial deflagration over time. The time between the images is 10 ms

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speed cameras (200 Hz). In comparison with current infrared sensors, however, its false alarm rate was too high.

In the current project, the camera system has been supplemented with infrared sensors already in use (Figure 2) to reduce the risk of false alarms. Due to the different detection methods of cameras and sensors, the overall risk of false alarms of the camera-sensor system is now even below that of a system that only relies on infrared sensors. In our tests in a mock crew compartment (Figure 3), all deflagrations were detected in their initial phase.

In addition, a customised localisation algorithm has been developed. This new algorithm is significantly more robust than previous methods and allows detection systems to operate under conditions with partially hidden and reflecting surfaces. A more efficient algorithm for estimating volumes has also been developed.

The computationally demanding parts of the algorithm have been ported from the CPU- and GPU-based implementation to a field programmable gate array. The computation time per image was thus reduced to a guaranteed, negligible value in the nanosecond range.

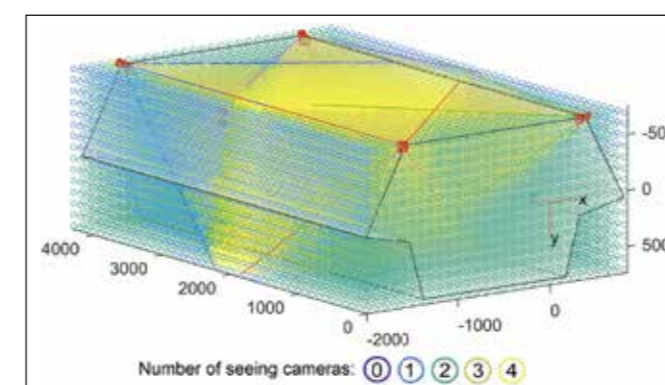


Fig. 2: Ideal camera positioning. Each point in space is observed by at least two cameras. Each camera also has an infrared sensor

On the whole, the resulting camera-sensor systems can now match sensor systems currently in use in terms of sensitivity, specificity and detection time. In addition, further information such as location and volume and development over time can be provided. The cost of the overall system has not, however, increased significantly.

The focus of further research will now be the exact application of water mist.



Fig. 3: Mock-up used for testing

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The impact of morale, welfare and recreation on health and motivation during deployment

Morale, welfare and recreation (MWR) are important factors that can maintain and enhance combat readiness during deployment. A project focussing on an evaluation of MWR revealed positive effects of different aspects of MWR (internet access, sports, entertainment, support) on health, commitment, motivation, and the intention to volunteer for another deployment.

Several individual and organisational factors affect the combat readiness of soldiers during deployments. While there is ample evidence for the importance of job characteristics (e. g. activity, working climate), the additional benefits of MWR have not been sufficiently studied, although they are considered to be important factors that may maintain and enhance combat readiness during deployment. A project conducted by the Bundeswehr Joint Forces Operations Command and a team led by Jörg Felfe and Wenzel Matiaske of the Bundeswehr University in Hamburg (2017 – 2019) examined the influence of different aspects of MWR (internet access, sports, entertainment, support) on physical and mental health, commitment, motivation, and the intention to volunteer for another deployment.

In order to gather valid information, the project team collected data and made observations directly in the operation areas. There were substantial differences between locations in terms of conditions and MWR. For example, outdoor sports activities are very limited in Gao, Mali, due to the heat (Figure 1). On Cyprus, there were air-conditioned tents with sports equipment (Figure 2). In Al-Azraq, Jordan, training conditions are



Fig. 1: Outdoor sports area in Gao, Mali (2018)



Fig. 2: Tent with sports equipment on Cyprus (2018)



Fig. 3: Military fitness container in Al-Azraq, Jordan (2018)

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perfect because of the moderate climate and modern facilities. Soldiers use the military fitness container for individual fitness training (Figure 3) and the sports ground for team sports such as football and basketball (Figure 4). The relatively newly camp there also has a spacious room for MWR, which is equipped with table football, a pool table, books, games and movies (Figure 5).

We collected data from N = 3095 Bundeswehr soldiers serving in different international missions. 7.8 % were female, and 51.1 % were under 30 years old. 30 % were junior enlisted, 50.4 % NCOs, and 17.3 % officers. Participation was voluntary, and response rates varied between missions (40 – 90 %). In the survey, we asked about demographic data, assessments of basic conditions, usage behaviour and satisfaction with MWR options, especially MWR communication options. Participants were also asked about their current well-being, their job and life satisfaction, their commitment to the Bundeswehr and their profession, and their willingness to volunteer for another deployment.

Findings from the survey confirm the important role of MWR for soldiers on deployment. Especially sports, entertainment, and the quality of internet and telephone connections appear to be important factors for the satisfaction, motivation and health of soldiers. MWR also play a role above and beyond demo-

graphic data and job characteristics. Although combat readiness is mainly determined by individual and activity characteristics, our study provides evidence for the relevance of MWR. Military organisations should therefore not underestimate the value of MWR when it comes to performance and motivation. Instead, they should systematically maintain and develop MWR programmes.



Fig. 4: Sports facility in Al-Azraq, Jordan (2018)



Fig. 5: MWR room in Al-Azraq, Jordan (2018)

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Influence of different flight parameters on the performance of airborne RN detectors

UAV-borne, spatial-resolved RN detection is a key element of CBRN (chemical, biological, radiological and nuclear) area protection. In the NATO defence against terrorism (DAT) project TEARS, the influence of different flight parameters such as velocity and height were investigated. Results show that flight movement causes detected values to deviate from ones derived from a stationary measurement setup.

With the growing use of unmanned, airborne vehicles (UAV) especially in intelligence and reconnaissance, the combination of a mini UAV with a payload of 1–5 kg and a custom RN sensor would be an enormous advantage in CBRN reconnaissance (Figure 1). Studies show that suitable detectors that fulfil requirements are not only commercially available but are specially designed for integration in airborne-based platforms. Available performance data for detection limits and energy resolution appear to be promising for integration on a UAV, but the values were gathered from a static 2D test setup in a laboratory and therefore may not be transferable to a dynamic 3D environment.

In the Test and Evaluation of Airborne RN Sensors (TEARS) project, which was supported by the NATO Counter Terrorism Section of the Emerging Security Challenges Division, Belgium (DLD, SKFCEN) and Germany (FKIE, WIS) developed a test procedure that takes in to account not only dynamic aspects of the situation during which measurements are taken but also operational requirements such as typical heights and velocities.



Fig. 1: Example of a mini UAV (left) and RN sensor (right)

In February 2020, the participating institutes carried out a test campaign at a closed test site in order to guarantee flight safety as well as radiation protection. UAV flew over different radioactive sources (Cs-137 and Co-60) that were placed on the ground at the test site. The chosen nuclides are typically used for the evaluation of common RN sensors.

The different flight paths that were used in the experiments varied in terms of height, velocity, lateral offset, and data acquisition rate. Owing to operational requirements (high risk of detection and engagement), flying heights below 20 m are not advisable. On the other hand, the maximum height is limited to 50 m, on account of detection limits of the sensor and typical source strengths.

Similar considerations apply to velocity. A slow velocity also increases the risk of detection and engagement but can be used at higher altitudes. We therefore investigated values between 5 and 50 km/h.

Figure 2 shows the detected maximum dose rate when the UAV flies straight over (a lateral offset of zero) a Cs-137 source at a height of 30 m and at velocities between 5 and 50 km/h. It can be clearly seen that the maximum dose rate decreases with increasing velocity. This shows that the detected dose rate is not only a function of height, as would be expected according to the inverse-square law, but also depends on velocity. A possible reason for this is that with increasing velocity the spatial distance of data acquisition points also increases as the time between measurements is constant, namely 1.8 s.

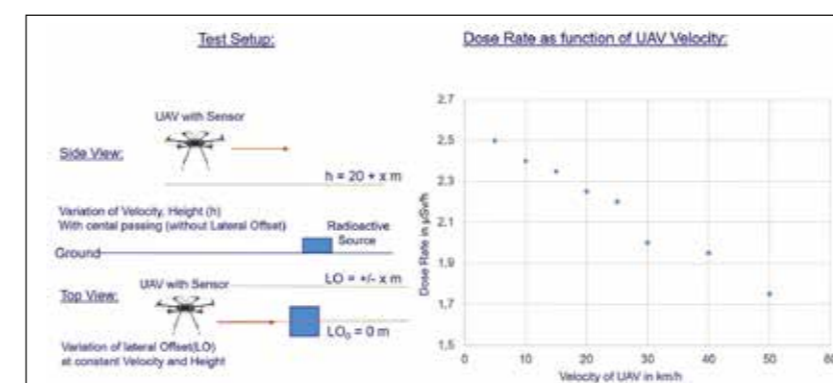


Fig. 2: Setup for the evaluation of airborne RN sensors (left). Maximum dose rate as a function of velocity (right)

At a higher velocity (above 5 – 10 km/h), the distance between source and sensor is therefore not necessarily represented only by the height. In scenarios with hand-held detectors and walking speeds (5–10 km/h), this effect can be neglected. For airborne sensors, this effect must be offset by mathematical modelling, or the spatial distance between data points must be kept constant, i. e. the data acquisition rate must increase with velocity.

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High-resolution and highly sensitive ion mobility spectrometer for unmanned aircraft systems

Interconnected sensors should be used in CBRN area protection to provide commanders as well as civilian emergency and rescue personnel with the best possible situational awareness. Sensors on UAS (unmanned aircraft systems) can make a decisive contribution. This article presents an ion mobility spectrometer (IMS) that has been optimised for use on UAS.

The unmanned aerial detection of chemical warfare agents and other hazardous substances makes significantly greater demands on sensor systems than operator-controlled systems, as direct intervention and control checks by operators are not possible during missions. These greater demands concern the electronic and mechanical reliability of the sensor system as well as its selectivity and sensitivity.

A dense network of sensors is required to establish a CBRN area protection system. The distance between sensors determines the time before a CBRN event is registered, the probability of detection, and the minimum detectable size of a release of CBRN materials. For this reason, a dense network would provide the best situational awareness and protection for own and allied forces against CBRN threats. Unfortunately, the price of sensors can hinder the construction of dense networks. The current prices of chemical warfare agent sensors range from a few thousand euros to tens of thousands of euros per unit.

One way to create a denser virtual network is to install sensors on highly mobile carrier platforms, especially UAS. Due to their



Fig. 1: Miniature IMS tube with non-radioactive ionisation source

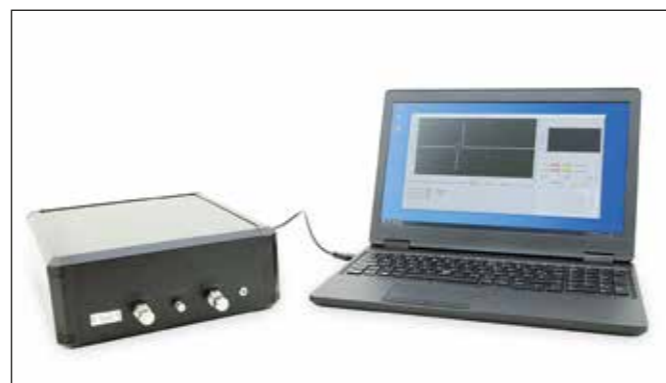


Fig. 2: Laboratory demonstrator for a miniature UAS-grade IMS system

high mobility, UAS can detect and identify dangerous substances and are able to record concentration profiles as well. The collected data can then be linked to propagation models and can be extrapolated into the past and the future, if necessary. This can indicate the source of hazardous substances and their initial concentration as well as the future spread of a hazardous substance cloud.

This approach imposes additional requirements on sensors, however, which cannot be fulfilled by existing systems. Today, ion mobility spectrometry is the most common sensor technology for the mobile detection of highly toxic hazardous substances such as chemical warfare agents. Ion mobility spectrometers are characterised by their small size and robust design. In addition, they are fast and sensitive. Existing commercially available IMS are, however, not particularly suited to use on UAS. They are designed to be carried and operated by a user. For a UAS-based application, existing IMS must be adapted to the requirements of a UAS mission. Apart from being lightweight and small, UAS-borne IMS should be able to detect highly diluted warfare agents at great distances from the source. Their selectivity must also be increased, as false-positive results cannot be verified by operators on site. Finally, the repetition rate of measurements must be high since this, together with the velocity of the UAS, determines the spatial resolution of the system. IMS must also be light and small.

For this reason, a miniature, highly sensitive IMS with high resolution was set up as a laboratory demonstrator and pre-characterised with hazardous substances as part of an R&T project on C(B)RN sensor sets. The ability of the system to detect various chemical warfare agents was investigated in 2020.

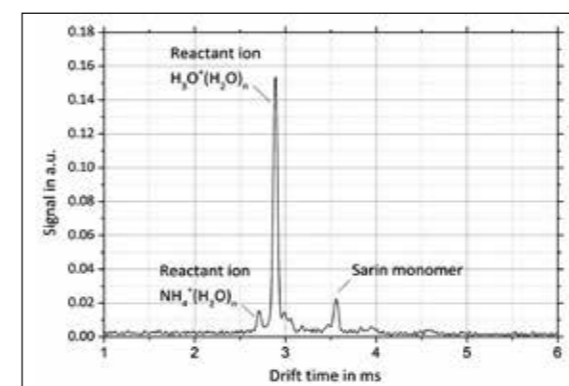


Fig. 3: Ion mobility spectrum of 390 pptv ($2 \mu\text{g}/\text{m}^3$) sarin in synthetic air

The very good results already obtained for “normal” hazardous substances were confirmed for chemical warfare agents. This modified IMS is significantly better than commercially available systems. A UAS-borne IMS system was developed on the basis of the laboratory demonstrator and will be characterised in laboratory and field tests in 2021.

If the results of the laboratory demonstrator can be reproduced with this new system in the planned experiments, this UAS-based IMS could make a decisive contribution to CBRN area protection.

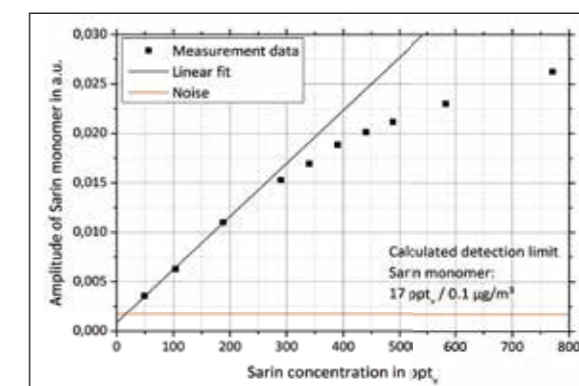


Fig. 4: Detection limit for sarin

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Use of artificial intelligence methods in additive manufacturing for interlinked product development

Machine learning and product development methods have been linked in a new approach to the computerised optimisation of high-performance components. This approach enables components to be optimised in parallel to meet various and often wide-ranging requirements. A large number of design variants have been created, calculated, and evaluated with the help of artificial intelligence for this purpose.

Research is being carried out at the 3D Printing Centre of the Bundeswehr to assess the potential of additive manufacturing for improving components. Computerised processes can be used to optimise components specifically for their function. With complex components that have multiple requirements such as strength, aerodynamic properties or manufacturability, the competing optimisation goals lead to mathematical problems that cannot be directly solved.

A new approach attempts to consider all requirements at the same time. To validate this approach, a drive unit of a current reconnaissance drone with a combustion engine has been optimised in close cooperation with the manufacturer. The goal is to reduce the number of parts of the drive unit, which currently consists of over a thousand individual components, to a significant load-bearing component and the necessary technical add-on parts.

The aim is to determine a weighting for the distribution of material in the design space and to observe all boundary conditions. The basis for distribution is a metamodel that

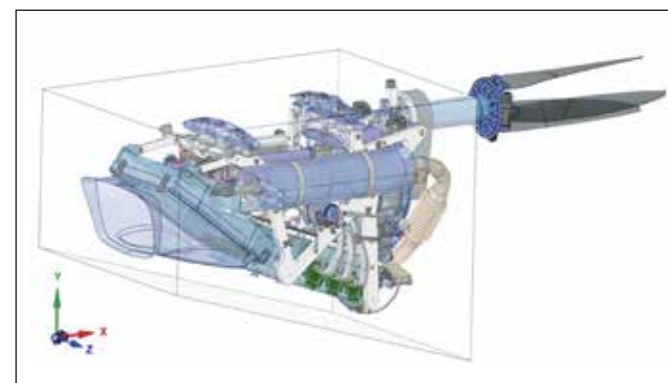


Fig. 1: Drone drive unit with derived design space

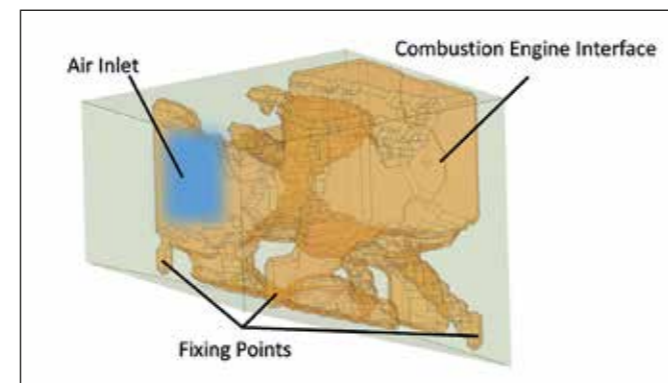


Fig. 2: Generic design with example constraints

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maps the properties and constraints required for optimisation. The metamodel is created through training examples in a learning sequence. A statistical model is built up using various algorithms. The procedure is divided into 5 phases.

The first phase deals with the loads associated with a real drive unit during operation. Design constraints such as the position of the internal combustion engine as well as the constraints of additive manufacturing are taken into account.

The second phase covers the creation of generic designs. The term “generic” means that a large number of design variants (in current calculations > 105) are automatically generated, taking into account all constraints and with a pseudo-random structure (i. e. without repeating mathematically recognisable patterns). In addition, there must be physical plausibility for every generic design. It is important that, for example, an FEM sensitivity analysis can be carried out with valid parameters.

The third phase is the sensitivity analysis. In this phase, the topological, aerodynamic and thermodynamic load profiles of each individual design are automatically calculated. In the implementation, automated simulations are carried out that run independently for all designs. The results are now available for all generic designs for all optimisation disciplines.

In the fourth phase, an artificial neural network is created from the training data. The created designs are used as a material distribution in a matrix as training input. Output comes from the simulation results. The weightings determined by training in the neural network now map the behaviour of the drive unit. A metamodel is thus created.

The probabilities that are recognised by the metamodel can be visualised three-dimensionally in the last step as a “heat map”. Spatial resolution is, however, still limited by the computing power available in current systems. In summary, the new approach makes possible the linking of mathematical optimisation functions via component functionality without a direct mathematical coupling of the solution functions.

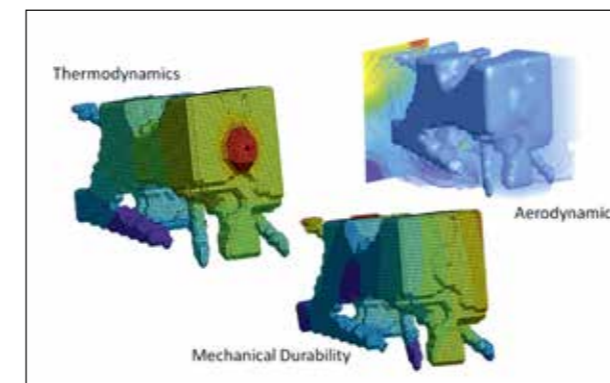


Fig. 3: Generic design evaluated for three requirements using FE simulations

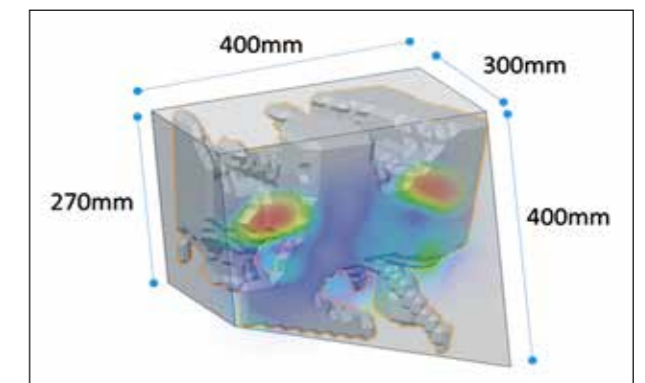


Fig. 4: Probability distribution of material of the metamodel in the design space

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Digitalisation of non-destructive inspection procedures

New technologies such as sensor tracking, augmented reality (AR), and digital twins show great potential for improving non-destructive inspection (NDI) procedures. HANGAR is designed to investigate the benefits of these technologies for NDI and to put them to use for the Bundeswehr.

Weapon systems need to be examined on a regular basis or after high-stress events in order to ensure safe operation. Depending on the material and the structural arrangement, different NDI procedures are used.

Modern aerial vehicles of the Bundeswehr, e. g. the TIGER support helicopter or the A400M transport plane, consist largely of carbon fibre reinforced plastics (CFRP). Since CFRP have only been used for a short period of time, sparse experience exists concerning its performance. For this reason, various well established NDI methods such as ultrasound and thermography are extensively applied.

The HANGAR (Highly Advanced Non-Destructive Testing with Gamification and Augmented Reality) research project aims to improve NDI performance and the digitalisation of testing procedures for military aviation. Enhancements are sought in ergonomics / usability, cost / benefit, measurement precision/reliability, and the reduction of the scope of training. In addition to digitalising data acquisition, procedures will be redesigned by integrating innovative technologies.



Fig. 1: Traditional state-of-the-art ultrasound inspection of a CFK structure



Fig. 2: Collaborative robot executing an ultrasound inspection of a CFK structure



Fig. 3: Real NH90 tail structure on the left, CAD model created via 3D-scan on the right

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In terms of information technology, non-destructive testing generally consists of data acquisition, data processing, and visualisation. These fields will be checked for improvement potential. A new laboratory environment with two working areas was created for this purpose. In one area, NDI methods such as ultrasound can be integrated into a robotic system (Figure 2) to automatically examine small test objects in a local coordinate system. The second area is a hall outfitted with a tracking system. The tail of an NH90 transport helicopter was placed in this area as a test object (Figure 3, left). The tracking system is used to determine and trace the positions of NDI sensors, people, visualisation devices, and other objects. The new laboratory makes it possible to optimise measurement methods and to apply them to a real aircraft structure.

The creation of digital twins allows us to correlate digital NDI data to their position on the test object. These contain current and previous NDI results, CAD data, and 3D scans (Figure 3, right). The explicit temporal linking of data acquisition and the related sensor position is the key to digitally archiving the inspection results, fusing them, and visualising them either in a virtual environment (VR) or on the real structure. Figure 4 shows an AR-aided ultrasound inspection. The user is provided with additional digital content that is projected onto his field

of view. Besides the real-time representation of NDT results, this information can include traditional inspection data that is usually shown on a mobile inspection system, test instructions, and geometrical properties of the test object (e. g. structure of the rear panel). The digital twin acts as an information source as well as data storage. While AR applications are especially suitable for the inspection and visualisation of the actual test object, VR provides more advantages for qualified location-independent damage assessments. As all information is centrally available, NDT data can be gathered throughout the weapon system's lifecycle and can be interpreted in a general context. In addition, dispersed workers can cooperate on a common database.



Fig. 4: AR-aided ultrasound inspection



Fig. 5: Actual view of an auditor in a virtual environment. Ultrasound C-scan integrated in a semi-transparent CAD model

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Establishment of assessment capabilities to study influences of flight control on highly contoured intake systems

The Institute of Jet Propulsion (ISA) at the Bundeswehr University in Munich and Bundeswehr Technical Center for Aircraft and Aeronautical Equipment have developed a highly curved, compact intake system for research purposes. Previous studies of the engine intake have been limited to ground-level cases. An ambient-condition-independent test bench has been designed and built for assessing complex intake systems in realistic flight conditions.

A previous proof-of-concept study examined the general conditions for developing a test bench for assessments of highly curved intake systems. Relevant parameters of flight conditions were identified by analytical calculations. A simulation tool chain was designed to transfer flight data to the intake's operating conditions, allowing Mach- and Reynolds-number conditions to be determined based on the thrust requirements of the aircraft.

The test bench was set up at the multipurpose wind tunnel of the Institute of Jet Propulsion. A scaled-down intake model (MediMEIRD – Medium-scaled Military Engine Intake Research Duct) was integrated into a pressure vessel (Figure 1). The performance data of the wind tunnel provide a dedicated experimental Mach- and Reynolds-number range, enabling the investigation of flight altitudes between 6 km and 12 km, as well as flight speeds up to Ma 0.95. The addition of a vacuum exhaust pump to the wind tunnel will allow for investigations of higher altitudes in the future.

The test bench concept (Figure 2) starts with an adaptive kidney-shaped inlet nozzle pushed over the intake at its outlet plane.



Fig. 1: Pressure vessel of the multi-purpose wind tunnel, mounted on a sliding carriage

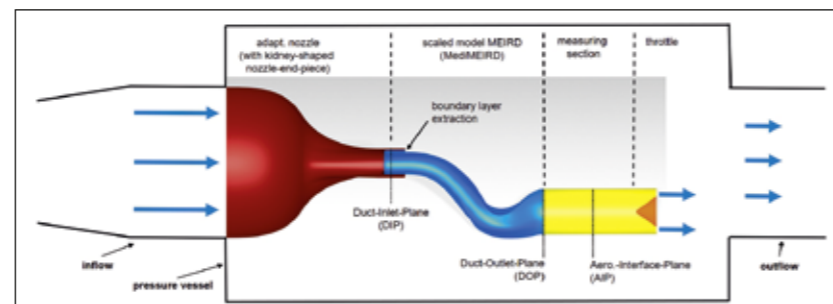


Fig. 2: Design of the experimental setup inside the pressure vessel with labelling of individual components

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This structure allows for the extraction of the inlet boundary layer, which results in a homogeneous flow at the duct inlet plane (DIP). The nozzle end pieces can be customised in various ways. They are designed to fit the 3D printing space at the Bundeswehr Research Institute for Materials, Fuels and Lubricants. A traversable measuring rake is located at the aerodynamic interface plane (AIP), followed by a hole pattern throttle for the fine adjustment of inlet discharge conditions. The operating point of the inlet and the backpressure in the vessel are adjusted using the bypass duct of the wind tunnel.

The instrumentation includes 188 pressure taps and a boundary layer measurement rake for analysing the flow separation region in the MediMEIRD (Figure 3). Pressure measurement points in the inlet nozzle and at the leading edge of the intake facilitate the study of the contraction of the nozzle and the control of boundary layer separation. Data acquisition and the control system are based on proven architectures at ISA and fit seamlessly into the existing data architecture. This ensures direct comparability of the results with other MEIRD experiments at ISA.

Detailed CFD assessments and design analyses were used to optimise the experimental test setup. For example, the contraction of the nozzle and the kidney-shape change were investigated by (CFD) simulations, thus ensuring a disturbance-

free flow at the DIP and inside the nozzle. This also leads to an optimisation of the effectiveness extraction of the boundary layer. The resulting super elliptical shape of the leading edge indicated behaviour insensitive to flow separation while maintaining the function of boundary layer extraction. The entire simulation of the test bench (Figure 3) showed the interaction of the components as well as the shaping of the boundary layer and vortex systems in the overall process. Comparisons of the vortex systems and the total pressure disturbance patterns at the outlet plane of the intake demonstrated an excellent match with previous investigations of the MEIRD. This correlation ensures the high comparability of results and validates the numerical setup as a powerful tool for supporting measurement campaigns.

The new test bench offers an extremely flexible test environment for future validation tests of complex intake systems and interaction phenomena. Furthermore, the test environment supplements the toolchains developed at ISA for designing and evaluating future aircraft propulsion systems and integration aspects. It opens up potential for product engineering support, from the definition phase to the utilisation phase, which has previously not been seen in the Bundeswehr.

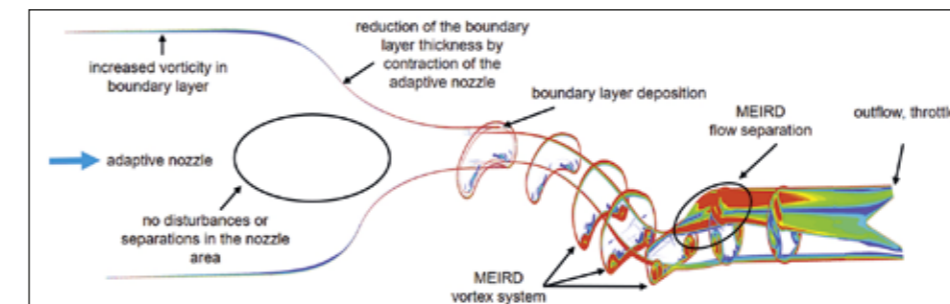


Fig. 3: CFD simulation result of the experimental setup, representation of the vorticity, labelling of investigated subareas

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PRS demonstrator for aviation applications and integration into air traffic management systems

A fully functional navigation warfare (NAVWAR) hardened demonstrator based on a Galileo public regulated service (PRS) receiver serves as a basis for initial R&D analyses and evaluations of Galileo PRS used for air traffic control and the airspace integration of unmanned military and civilian aircraft. Initial tests have been conducted in cooperation with German Air Traffic Control.

The Bundeswehr is planning to operate both manned and unmanned (military) aircraft (UAS) in civilian airspace. For this reason, military requirements regarding PNT (position, navigation, timing) with reference to navigation warfare must be determined at an early stage in order to be incorporated into development processes of UAS airspace structures and air traffic management concepts. One domain of these R&D considerations is concerned with the integration of military UAS into common (civilian) airspace structures. This includes an analysis of air traffic management (ATM) systems and UAS traffic management (UTM) systems that are currently in development.

The following R&D study focuses on a fully operational UTM system developed by Droniq GmbH, a joint venture of DFS (which is responsible for air traffic control in Germany) and Deutsche Telekom. The UTM processes position data from UAS in real time and merges them with location data of traditional (manned) aviation into a comprehensive traffic management aerial view (Figure 1). In addition, the UTM offers further functions for the safe operation of drones in German airspace



Fig. 1: Comprehensive traffic management aerial view (TrackViewer of DFS) with traditional (manned) aviation aircraft (green circle) and unmanned aircraft (red circle)

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such as mission planning and includes collision warnings. In the future, the UTM system will also be used to map the entire workflow for conducting drone missions. This will result in synergetic approaches to military and civilian UTM (traffic control).

A small HOD4Track is required for this approach. The HOD4-Track can easily be attached to UAS and transmits the GNSS-based position data via 4G/ 5G to the UTM system of DFS. To protect highly automated, critical UTM navigation applications, non-disruptive navigation systems are necessary. Such systems are not, however, publicly available yet. In order to resolve this issue, this R&D study is investigating the encrypted and robust Galileo PRS as a secure GNSS source for UAS airspace structures and traffic management concepts. During this study, the HOD4Track was upgraded by a (classified) Galileo PRS demonstrator (Figure 2) that ensures the determination of secured (non-spoofable) UAS position information. In addition, this Galileo PRS HOD4Track prototype was integrated into the UTM system of DFS. As part of the demonstration, the safeguarding of the UAS traffic control system against spoofing for drones was shown.

In a second step, this R&D study demonstrated a server-based PRS application in order to outsource the processing of classi-

fied data from the UAS to a secure infrastructure (future DFS infrastructure). Plans have been made to continue this R&D study with consideration for approval of the PRS processing server operation in coordination with regulatory authorities and the Federal Cyber Security Authority. The current system architecture is shown in Figure 3 and consists of three sub-components. The PRS snapshot receiver on top of the drone generates short snapshots of RF signals (approximately 10 ms), which are sent to a remote server at the Fraunhofer Institute for Integrated Circuits for PRS evaluation. At the same time, an integrated open service (OS) receiver is used to transmit OS-based PNT information directly to the UTM system of DFS. The remote server uses its Galileo PRS security module to evaluate and process the received snapshot data and distributes the secure, protected PNT results to the DFS UTM system. By comparing these two PNT solutions, the DFS monitor is able to detect spoofing using the secure PRS-PNT. The result is shown as an overarching airspace traffic situation picture represented by the Droniq TrackViewer monitor in Figure 1.

The overall project was also submitted to ESA's CESA R&D programme as a success story in connecting IoT and Galileo applications.



Fig. 2: Prototype HOD4Track demonstrator using Galileo PRS as a countermeasure to GNSS spoofing

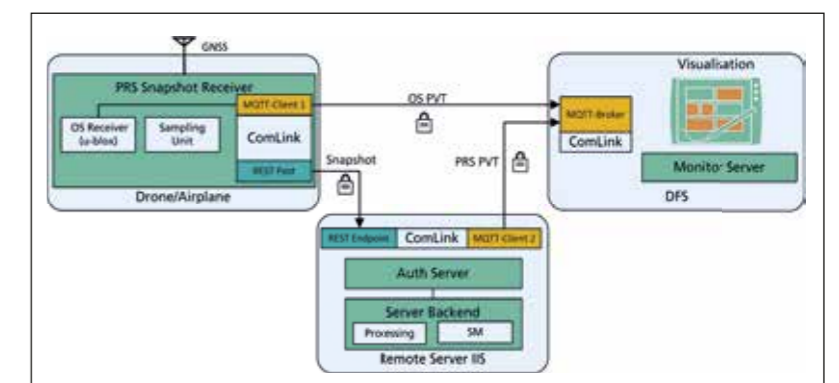


Fig. 3: System architecture of OS demonstrator with a server-based PRS application

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Maritime unmanned systems for anti-submarine warfare

Smart, easily deployable, unmanned and self-sufficient mobile and stationary systems that are connected in heterogeneous wireless ad-hoc underwater networks are suitable for protecting ships and harbours and for the surveillance of straits (choke points) against underwater threats. In this way networked systems enable a comprehensive reconnaissance under water.

The use of modern, multistatic sonar, whereby multiple sonar sensors (either passive or active ones) placed at different locations work cooperatively together, is a proven concept in anti-submarine warfare (ASW) for countering the threat posed by modern low-signature submarines.

The Bundeswehr Technical Centre for Ships and Naval Weapons, Maritime Technology and Research (WTD 71) has investigated the potential of maritime unmanned systems to assist manned platforms in modern ASW or even to execute parts of this task independently. Measurement systems were developed, as were signal-processing algorithms for autonomous detection, localisation and tracking. These unmanned systems are able to generate information from recorded acoustic and non-acoustic sensor data and to report this information to a centralised or decentralised multi-sensor data fusion engine via an ad-hoc underwater acoustic communication network (Figure 1). Figure 2 shows an automatically generated acoustic target detection – here: bearing and broadband power levels over time.

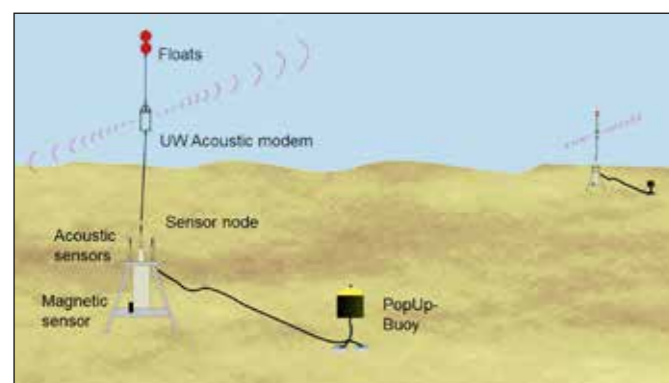


Fig. 1: Stationary unmanned measurement systems in a network for underwater surveillance

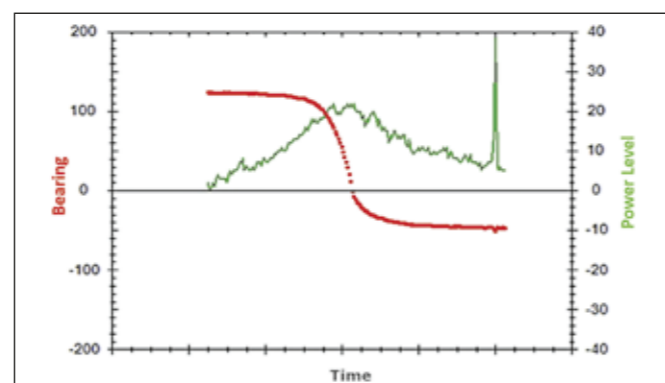


Fig. 2: Automatically generated acoustic detection: bearings vs. time (red) and broadband power level vs. time (green). The high power level at the end of the reported detection resulted from an incoming underwater message from a neighbouring system

Modern adaptive signal processing algorithms enable increasingly intelligent autonomous systems. The long-term objective is a system with humanlike analytical capabilities. Robust, long-range, encrypted and covert acoustic communication with – depending on the application – highest possible data rates is required for reliable data transfer under water. But these requirements are mutually dependent and continue to be the focus of current research.

New emerging sensor technologies, e. g. acoustic vector sensors, may further increase the potential of unmanned systems. Vector sensors measure both the acoustic pressure (as common hydrophones) and the sound particle velocity (x, y and z component). For this reason, a single vector sensor can estimate the direction of arrival of incoming sound waves, something that would otherwise require an array of hydrophones.

Compared to conventional sonar arrays of hydrophones, the same number of elements in vector sensor arrays can lead to significant increases in performance. Similar performance can be achieved with a considerably lower number of vector sensor elements. Vector sensors and vector sensor arrays are thus especially useful for smaller systems that are limited in terms of space and resources. This includes in particular small-sized maritime unmanned systems.

After conducting small-scale tests, the Bundeswehr Technical Centre for Ships and Naval Weapons, Maritime Technology and Research conducted a multi-day sea trial in the Baltic in 2020. In this trial, an autonomous vector sensor array system (Figure 3 on the left) was tested for the first time. Issues such as the impact of various array designs and different beam-forming algorithms

were investigated, and the potential of vector sensor arrays compared to hydrophone arrays was studied. Acoustic data was processed inside the sensor node in real-time so that broadband noise traces of surface vessels could be detected and tracked (Figure 3 on the right).

Maritime unmanned systems will also be used in multinational heterogeneous sensor networks for underwater surveillance. This will be done in cooperation with NATO partner nations, for example in the Distributed Autonomous Networked Systems research project (in preparation) and as part of the NATO Maritime Unmanned Systems Initiative (MUS I). The focus is on multinational interoperability in underwater ASW networks, the development of NATO standards and doctrines, and joint demonstration and validation at sea.

Maritime unmanned systems have demonstrated their high potential for underwater surveillance already. In the future, more powerful systems and systems of systems can be expected with regard to intelligent signal processing algorithms, communication links, and endurance capability.

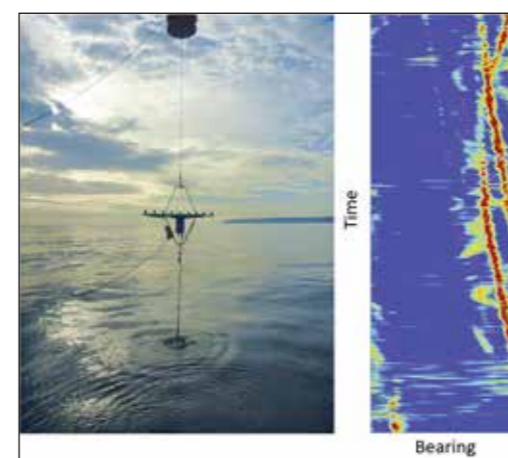


Fig. 3: Unmanned acoustic vector sensor system in the deployment phase (on the left) and examples for target tracks (on the right)

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Influence of resonance effects on target echo strength

In active SONAR applications, the backscattered sound intensity (target echo strength, TES) is an important factor for the probability of detection of underwater objects. Some obstacles under water (e.g. gillnets) show a very small TES, resulting in more challenging detection. Resonance effects make it possible to significantly increase the probability of detection of such objects.

In order to expand knowledge about the TES of underwater objects, an object was needed which could be used to compare theoretical calculations with experimental results. For this purpose, militarily unclassified resonant spheres were fixed to a gillnet. Resonance effects play an important role in mechanics, acoustics and other areas of physics. For example, resonance effects are used in the design of musical instruments to amplify the sounds of an instrument.

In active sonar applications, sound waves are transmitted in order to detect underwater objects like submarines, torpedoes or unmanned underwater vehicles (UUV). They strike such underwater objects and are reflected back. With the use of hydrophones, the reflected sound intensity can be measured for different frequencies and positions. To transform this reflected sound intensity into a quantity independent of distance, it is normalised to a distance of one metre from the target and is called target echo strength.

This project uses theory and experiments to investigate how resonance effects can influence the TES of an underwater

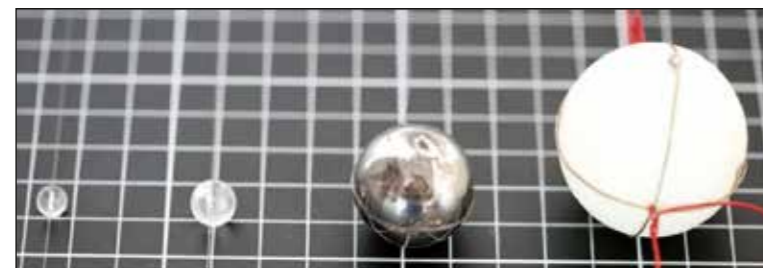


Fig. 1: Examined spheres: 2 x PMMA (solid), steel (solid), table tennis ball (air filled)

sphere data			
material	radius	maximal TES	TES diff
PMMA	3.2 mm	-40 dB	+16 dB
sound hard sphere	3.2 mm	-56 dB	
PMMA	4.8 mm	-36 dB	+16 dB
sound hard sphere	4.8 mm	-52 dB	
steel	12.8 mm	-42 dB	
sound hard sphere	12.8 mm	-44 dB	
air	19.0 mm	-37 dB	
sound hard sphere	19.0 mm	-40 dB	

Fig. 2: Properties of spheres of different sizes and materials

object. With a sufficiently large effect, small objects could simulate the TES of significantly larger objects in the region of their resonance frequency. Currently, the German Navy is using an icosahedron to conduct sonar performance tests. Its large TES is due to acoustic triple mirrors instead of resonance effects.

A normal gillnet used in fishing has a low detection probability and therefore may not be seen by submarines and UUVs. Small spheres were integrated into the net in order to significantly increase its TES when ensonified near the resonance frequencies of these spheres. This would allow underwater vehicles to detect gillnets early on and to avoid them. This affects the main purpose of the gillnet only minimally. The unwanted bycatch of whales, which can also better detect the modified nets, could also be considerably reduced. Together with the Thünen Institute of Baltic Sea Fisheries, these effects are being investigated in practice.

Spheres of different diameters and materials (Figure 1) were examined in numerical analyses and experiments. The table in Figure 2 shows the chosen materials and radii. The two larger non-resonant spheres reflected the incoming sound intensity nearly completely and therefore acted as ideal acoustically hard and soft spheres that exhibit a frequency independent TES of -44 dB and -40 dB. These values have been confirmed by experiments (Figure 3). The polymethyl methacrylate (PMMA) spheres show a distinct increase in TES at a certain resonance frequency, which results in higher frequencies in TES values comparable with the significantly larger spheres. This effect was also confirmed with experimental data (Figure 3).

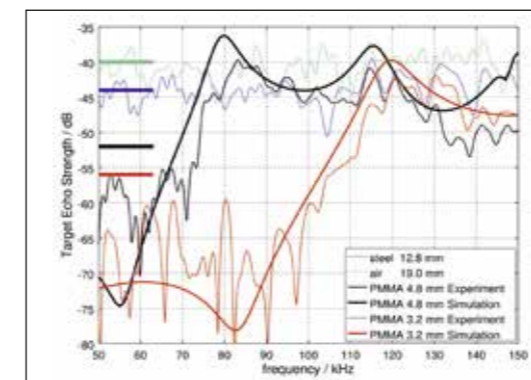


Fig. 3: Simulation and measurements of target echo strength of the various spheres

Since an acoustically hard sphere completely reflects the incoming active intensity, we must ask ourselves where the additional intensity for the smaller PMMA sphere is coming from. This can be understood (Figure 4) if we look at the streamlines (black) of the active intensity for three different frequencies. Due to the resonance, the effective active radius (cross section) of the sphere (grey) in the sound field increases significantly close to the resonance frequency. By fixing several such spheres to a gillnet, the target echo strength and therefore the probability of detection can be noticeably improved.

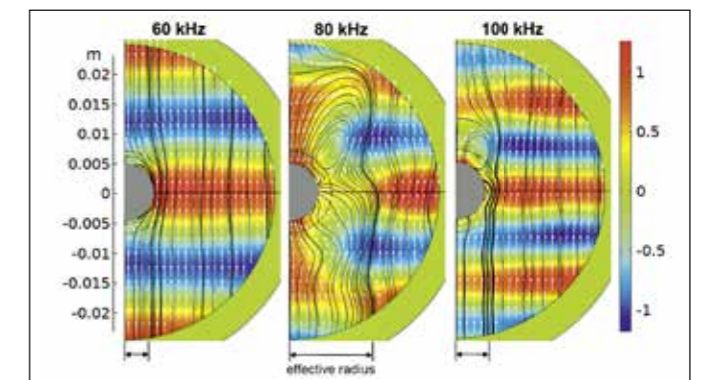


Fig. 4: Incoming active sound intensity during insonation of a PMMA sphere with a radius of 4.8 mm at frequencies without (60 kHz) and with resonance effects (80 kHz)

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High-speed impacts on high-strength concrete

Over the last two decades, research on advanced construction techniques has intensified. High-strength concrete has been identified as a means of choice for protecting hardened facilities such as bunkers. Weapon systems are now being developed to counter these gains. Our research is aimed at understanding effects during penetration into high-strength concrete in order to feed modelling and simulation tools with appropriate data.

The protection of important facilities has a very long history. Castles and fortresses are witnesses of a bygone era. Even today, the ruins of such buildings elicit admiration and astonishment. They have been overtaken by time. Bunkers built in the Second World War are the most recent relics of attempts to create ultimate protection. Unlike buildings of the Middle Ages, these bunkers still withstand the demolition activities of modern times. This must not distract from the fact, however, that activities in the field of protection have never come to a halt.

Since the Second World War and especially in the last twenty years, research has been carried out around the world on improvements in concrete structures, manufacturing processes, and concrete mixtures. Bridges and other infrastructure components have benefited from this progress, as have protection systems. The use of high-strength concretes has increasingly been the focus of investigations. These are concretes to which (steel) fibres have been added. The fibres are designed to make an inner “hook” in the matrix. Reinforcement as in old concretes is no longer necessary. New shapes are thus possible without any concessions to stability, hardness and strength.

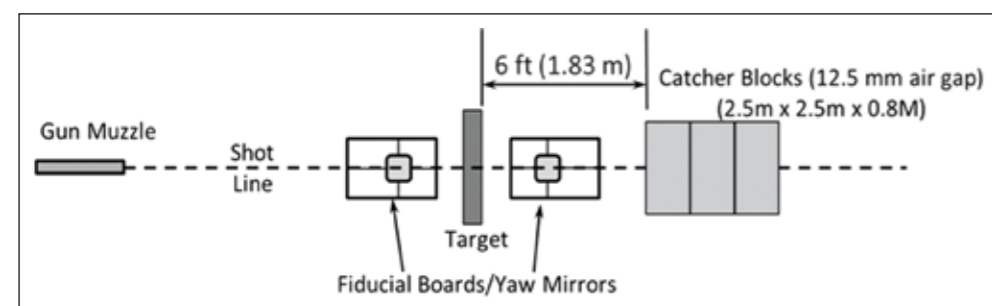


Fig. 1: Test setup

These new capabilities open up numerous possibilities for designers of protective structures. Components can be created in advance and then assembled as in a modular system. Casting at the construction site is no longer necessary. Structures far away from otherwise necessary infrastructure are now possible. This is an unforeseeable boost for the building of command structures.

Legacy weapon systems are optimised against materials that do not correspond to new materials and processes and thus cannot be completely successful. In order to promote new developments, we must study the processes involved in the penetration of these novel materials. Only then can the various simulation tools be adapted accordingly. These tools are simulation programs for mission planners and programs for engineers.

As part of a project between the United States and Germany, basic studies were carried out on the behaviour of subscale-calibre penetrators in high-strength concrete at the Bundeswehr Technical Centre for Weapons and Ammunition. In two trials, targets weighing 7.5 tons to 29 tons were tested at four different speeds. The projectiles carried two different and independent measuring devices. The projectiles were fired from a 120 mm gun of a battle tank.

In the first trial, projectiles were shot at three targets of different thicknesses at two different speeds. The targets had a diameter of 2.40 m and thicknesses of 0.61 m, 1.22 m and 1.83 m (2 ft, 4 ft and 6 ft). The speeds were about 1500 ft/s and about 3000 ft/s. The recorded accelerations were evaluated and integrated into the current simulation tools.



Fig. 2: Projectile flight



Fig. 3: Pre-test result

A second measurement trial was carried out to validate the updated modelling and simulation tools. In this series of tests, targets of the same mixture with a diameter of 2.40 m were used. The thickness values this time reached up to 2.44 m. Speeds were increased to 3700 ft/s. Similar to the first series of measurements, “pluggers” as well as “shot throughs” were deliberately generated. The data obtained from the partly improved measuring electronics will now be reintegrated into the simulation tools.

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Further development of military training areas

Digitalisation in the Bundeswehr continues to move forward. Although military training areas have been neglected in recent years, the focus has now shifted to their digitalisation. With the help of interconnected applications, capability gaps will be closed in order to realise future-oriented and mission-oriented combat exercises. The Bundeswehr Technical Centre for Weapons and Ammunition is conducting R&T studies in this field.

Further Development of Military Training Areas and Firing Ranges is a project designed to digitalise German military training areas over the next few years. The expansion of Firing Range 3 in Bergen was a starting signal for this project.

The Bundeswehr Centre for Weapons and Ammunition has been tasked with conducting research and development in the field of digitalised military training ranges. A test bed is being set up at the centre which is suitable for conducting such research.

In order to implement a digital, enhanced military training area, the following core technical elements are required:

- IP-based communications infrastructure, e.g. 5G, LTE, WLAN, fibre, cable, etc.
- interconnection of all participants, e.g. leaders, exercisers, targets, range safety, shot detection, etc.
- software applications
- security planning, security management
- central data management system, database, server, cloud, open and standardised interfaces



Fig. 1: Autonomous target robots



Fig. 2: Firing exercise at Wildflecken

- exercise control and evaluation
- target display devices with sensor technology and weapon sensor technology which are mobile, self-moving, stationary, adaptive, and interactively controllable.

The results of R&T activities were presented to high-ranking military guests at a combat firing event by the Bundeswehr Technical Centre for Weapons and Ammunition in cooperation with Fraunhofer EMI on 30 September and 1 October 2021 at Firing Range 16B in Wildflecken.

The following components and technologies were interconnected for the event:

- autonomous moving infantry targets
- digitalised flip-up targets
- real-time hit detection
- real-time display of target means on tablets and hardened laptops
- battlefield reconnaissance via drones
- blueforce tracking via smartphones.

With the help of these components, a tactical combat scenario was implemented according to the specifications of the firearms instructor of the guard battalion. The scenario was programmed in advance. Due to the tracking of own troops, the target setup can be controlled interactively, for example the target robots can act independently depending on position or firing.

In addition to the pre-programmed scenario, the firearms instructor is also able to control targets directly via a tablet. An important aid for effective training is the integrated hit-detection sensor system, which accurately displays both hits



Fig. 3: Real-time display

and misses and provides the shooter with direct feedback on the aiming point and the shot location.

Train as you fight – this motto takes on a completely new meaning thanks to new technology. Training will become more effective and successful because soldiers will receive more realistic training. This was impressively demonstrated at the first “digital” firing exercise.

The findings and lessons learned from such R&T activities and practical trials will flow directly into the Customer Product Management process.



Fig. 4: Presentation for the Chief of the Joint Support and Enabling Service

2

Military Medical and Military Psychology Research

The year 2020 was defined by the COVID-19 pandemic, including when it comes to military medical research. In March 2020, the Bundeswehr Medical Service had already initiated a research programme to ensure that pandemic-related military medical research could be conducted swiftly and with a focus on the relevant issues. There are several examples of the contributions of the Bundeswehr Medical Service to the global research effort in the fight against COVID-19. The Bundeswehr Institute of Microbiology has developed a diagnostic capability for SARS-CoV2 for use on ships at sea. The Bundeswehr Institute of Radiobiology has established additional capacities for SARS-CoV2 testing. The Bundeswehr Central Hospital in Koblenz has developed a high-throughput testing capability. The Bundeswehr Hospital in Ulm has conducted research on autoimmune antibodies as a risk factor for severe progression of COVID-19.

Beyond the scope of COVID-19, research institutes and hospitals of the Bundeswehr have also contributed other excellent research in aid of protecting and restoring the health of Bundeswehr soldiers.

The Bundeswehr Institute of Pharmacology and Toxicology reports on the adverse effects of sulfur mustard poisoning on regenerative stem cells, which results in delayed or incomplete wound healing. The Bundeswehr Institute of Preventive Medicine introduces a new methodology for assessing the physical fitness of active soldiers and applicants for military service. The Naval Institute of Maritime Medicine describes the effects of hyperbaric oxygen on the immune system and potential consequences for the health of military divers. The Air Force

Centre of Aerospace Medicine, on the other hand, conducts research on the effects of hypobaric oxygen at high altitudes, using a specialised chamber for artificial altitude exposure.

In addition to the work of these research institutes, intensified research at Bundeswehr hospitals has increasingly come to form another important pillar of military medical research.

The Bundeswehr Hospital in Berlin describes the evaluation of different simulation methods used to train life-saving surgical procedures, the use of online video consulting between patients and their doctor and the development of advanced osseointegrated prosthetic systems. The Psychotrauma Centre at Berlin Bundeswehr Hospital conducts research on equine-assisted therapy in the treatment of PTSD. The Bundeswehr Hospital in Hamburg presents its work on evaluating molecular diagnostic methods for tropical parasitic infections.

The COVID-19 pandemic was also relevant for military psychological research in 2020. The Psychotrauma Centre at Berlin Bundeswehr Hospital highlights a civil-military collaboration that examined the impact of the pandemic on anxiety, aggression and anger among hospital staff and a high-risk population affected by COVID-19.



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Welcome aboard: SARS-CoV-2 diagnostics on the high seas

In the cramped conditions on board ships and boats, cases of COVID-19 can quickly multiply. The Bundeswehr Institute of Microbiology, in cooperation with the Navy Medical Service, has therefore developed detection methods for the reliable diagnosis of SARS-CoV-2 based on PCR tests directly aboard sea-going units.

The rapid global spread of SARS-CoV-2 posed enormous challenges, particularly for the Navy Medical Service. On board ships, COVID-19 infections can spread rapidly. Mission fulfilment can be jeopardised when patients require treatment and containment measures become necessary. Access to laboratory services on land is also limited. Rapid on-site testing is therefore particularly important in maritime operations.

In early April 2020, the Navy Medical Service tasked the Bundeswehr Institute for Microbiology (IMB) with immediately installing COVID-19 diagnostic capacities on the FGS Berlin, a combat support ship of the German Navy. The challenge was to provide at short notice a laboratory procedure to establish and validate PCR testing on relatively simple Navy equipment with only two fluorescence channels and to transfer all materials to the FGS Berlin in time. After an identical PCR device was delivered to the IMB in Munich after only a few hours, the first test runs could start the next day. After validation on patient samples, the reagents, operating instructions and software for device programming were packed in air- and water-tight boxes and transported by Navy helicopter to the FGS Berlin, which



Fig. 1: Special package on the flight deck; a Sea King Mk41 helicopter of Naval Air Wing 5 from Nordholz makes a last-minute delivery of special, temperature-sensitive reagents for COVID-19 testing on 8 April 2020 (source: 2020 Bundeswehr/Dr. Laumann)



Fig. 2: Video conferencing with the FGS Berlin; the possibility of providing telemedical advice for sea-going units, which was established years ago, greatly facilitated the briefing of personnel on board (source: 2020 Bundeswehr/Dr. Wölfel)

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was already cruising in the North Sea (Figure 1). Immediately on arrival, a medical-technical laboratory assistant (MTLA), who had embarked especially for this purpose, was able to perform a first test run. This first system test, telemedically supervised from Munich, was successfully completed just five days after the first development order (Figure 2).

However, the availability of laboratory personnel turned out to be a critical factor in the further course of the project. The MTLA who had embarked from Kiel had to leave the ship after only a few weeks. In the summer of 2020, however, the first point-of-care PCR tests (POCT) to not require special laboratory experience became available. The IMB was therefore once again commissioned to evaluate the performance parameters of a PCR device designed as a POCT system for possible use in the German Navy.

Because of the imminent deployment of the FGS Hamburg (Figure 3), there was once again only a narrow time frame of a few days to carry out the evaluation. In the short time available and in an all-hands-on-deck effort, a total of 199 test runs were carried out at the IMB with the equipment to be evaluated. In comparative testing against an established PCR system from routine laboratory-based diagnostics, using standardised SARS-CoV-2 culture material and precisely quantified RNA preparations, the detection limit of the POCT system was close

to that of the routine PCR system. The POCT system also achieved significantly better results when compared with antigen rapid tests in particular, which were also investigated at the IMB.

In both these instances, the IMB as a governmental research institute was able to quickly derive practical applications from ongoing research work thanks to its focus on translational science. Examples such as these demonstrate the advantages of gearing the most modern military medical research capacities to the needs and applications of the armed forces. With these capabilities, the Bundeswehr is well prepared for future challenges.



Fig. 3: FGS Hamburg; the ship's sickbay was equipped with a system for point-of-care testing for COVID-19 at the end of July 2020, just before the deployment of EUNAVFOR MED Irini (source: 2008 Bundeswehr/Winges)

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Impairment of regenerative stem-cell function by sulfur mustard poisoning as a possible cause of chronic wound healing disorder

The Bundeswehr Institute of Pharmacology and Toxicology studies the toxicity mechanisms of chemical warfare agents in order to develop antidotes. In recent years, the blister agent known as sulfur mustard has repeatedly been used in Syria. Damage to the regenerative stem cells has been identified as a possible cause of resulting chronic wounds.

The chemical warfare agent known as sulfur mustard (SM) damages mainly the eyes, lungs and skin. After a clinical latency period without symptoms, which can delay rapid and efficient decontamination, erythema and then blistering of exposed skin occur. Wound healing is critically delayed and, especially in cases of severe poisoning, chronic wounds develop which may require skin grafting. Because its chemical synthesis is so simple and because of remaining stores from World War II, there is still a very real danger of SM being used for terrorist purposes, even though chemical warfare agents are internationally banned by the Chemical Weapons Convention.

Especially due to its complex mechanisms of action and damage, SM poses a challenge when it comes to developing a causal treatment. The resulting treatment gap highlights the need for research to improve treatment and develop antidotes.

Since the main problem after SM exposure is impaired wound healing, it seems likely that regenerative endogenous stem

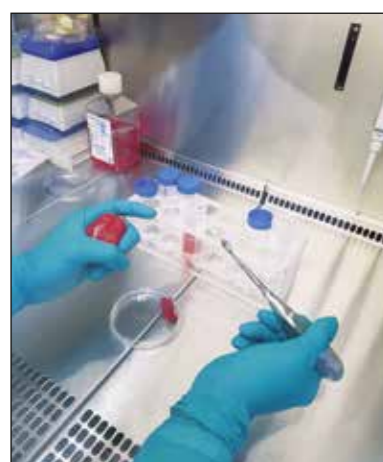


Fig. 1: Isolation of human mesenchymal stem cells from bone marrow of femoral heads

cells are affected by SM. Mesenchymal stem cells (MSCs), which play an essential role in the healing of skin wounds, are recruited after tissue damage and have a modulatory and regenerative effect through various mechanisms. The Bundeswehr Institute of Pharmacology and Toxicology in cooperation with the Helios Amper Clinic in Dachau established a procedure for isolating MSCs from human bone marrow in order to study them directly (Figure 1). For this purpose, we use femoral heads harvested from patients undergoing hip replacement, which would otherwise be disposed of.

Our latest findings show that SM poisoning causes senescence in MSCs. Cellular senescence was first described in the context of ageing and was attributed to the shortening of telomeres, the “protective caps” of chromosomes. Senescence can also be induced by unrepaired DNA damage or oxidative stress. Both are core components of the mechanism of toxicity after SM poisoning, which suggests the hypothesis of SM-induced senescence.

In fact, we were able to show that a single-dose exposure to SM at concentrations too low to induce blistering can already trigger senescence in human MSCs (as shown by the blue staining in Figures 2 and 3). These senescent cells are no longer able to divide and show significantly reduced migration. They also secrete a variety of proinflammatory factors. SM poisoning could therefore damage the regenerative stem cells in such a way that they not only are no longer able to migrate to the tissue damage but also cause a chronic inflammatory response in the tissue. Thus, SM-induced senescence of MSCs could possibly be the cause of chronic wounds associated with SM exposure. Selective elimination of these cells should therefore improve

wound healing. In this innovative therapeutic approach, ABT-263, an inhibitor of anti-apoptotic proteins, has shown initial potential.

The newly identified pathomechanism of SM-induced senescence in MSCs opens up new therapeutic opportunities. In the long term, various substances will be tested to improve the impaired wound healing associated with SM poisoning. Such a causal therapy for affected soldiers, especially in connection with operations abroad, is urgently needed.

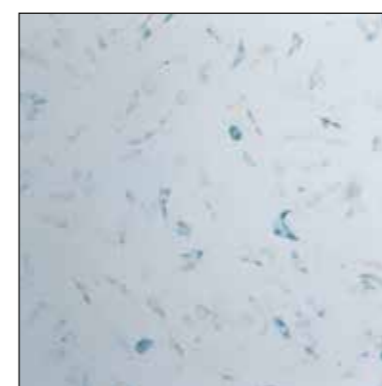


Fig. 2: Non-senescent mesenchymal stem cells

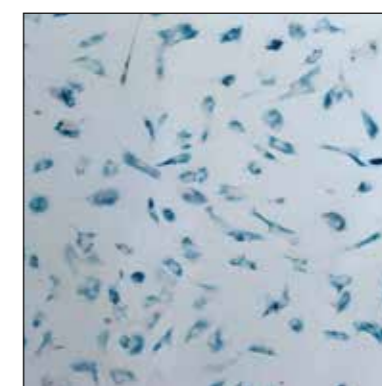


Abb.3: Senescent mesenchymal stem cells 21 days post exposure to 40 μM sulfur mustard, stained using senescence-associated β-galactosidase as a marker

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Efficient and valid assessment of physical performance in personnel recruitment and military medical assessments: The new CT-PF procedure

Negative social trends in health and fitness have increasingly come to affect soldiers. The correct assessment of physical fitness is therefore becoming all the more important. The new CT-PF procedure is an efficient and valid method well suited for the context of personnel recruitment and military medical assessments.

Many physically demanding tasks that are typical in military training and operations, such as marches, field training with equipment or rescuing the wounded, require high levels of strength, endurance and speed. Adequate physical fitness is both a prerequisite for the successful accomplishment of many military tasks (performance aspect) and an important factor in the long-term maintenance of health and physical fitness (prevention aspect). Physical fitness is thus the basis for acquiring and maintaining operational readiness.

For years, however, hours spent sitting at work, in traffic and at home as well as other unfavourable everyday habits have been adversely affecting the health, resilience and physical fitness of the general population as well as many soldiers. Given the physical demands of serving in the Bundeswehr, reliable procedures for determining physical fitness are therefore becoming increasingly important but, in the context of personnel recruitment and military medical assessments, should tie up minimal resources in terms of personnel, time, equipment and infrastructure.



Fig. 1: The parameters of the CT-PF require few resources to collect and are the strongest predictors for the conditional abilities strength, speed and endurance in relation to a standard military requirement profile

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Against the background of these requirements, the Bundeswehr Institute for Preventive Medicine, the German Sport University Cologne and the University of the Bundeswehr Munich developed a categorisation tool for physical fitness (CT-PF), with which physical fitness can be assessed and classified into three performance categories based on easy-to-determine predictors. As part of the joint research project, predictors for strength, endurance and speed were preselected and tested via multiple linear regressions against a general military requirement profile (basic military fitness tool, BMFT) as a reference criterion. The final parameter selection was made (i) with regard to the variance explained of the criterion SGT total time and (ii) taking into account requirements in terms of personnel, time, material and infrastructural resources.

The predictors of the CT-PF (fat-free mass, isometric maximum strength of the arm flexors and hand grip muscles, sprint test and 1000-metre run of the Bundeswehr Basic-Fitness-Test, gender, Figure 1) explain over 70 % of the variance (corrected R^2 : 0.71) and allow a sufficiently accurate prediction of physical fitness with reference to a general military requirement profile.

The CT-PF is an efficient and practical method for valid and reliable categorisation of physical fitness based on a traffic-light system (green / yellow / red) for specific physical requirements

of assignments (Figure 2). Because it requires only limited resources in terms of time, personnel, material and infrastructure, it is ideally suited for use in personnel recruitment and in military medical assessments.

CT-PF can, for example, be used as part of the recruiting process to provide recruits with a training tailored to the individual fitness needs. This could also reduce the dropout rates in basic training.

The CT-PF can provide valuable additional information for military medical assessments. The combination of health and performance data opens up a wide range of options when it comes to prevention, training and preparation for deployment. It could also contribute towards an important and currently unavailable operational picture for the leadership of the Bundeswehr.

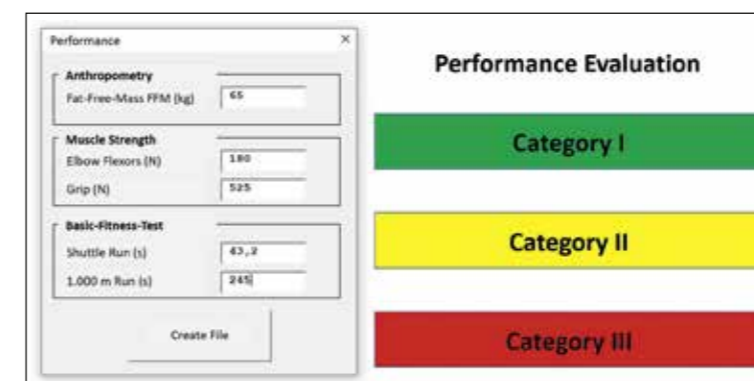


Fig. 2: Based on the collected data, performance can be validly and reliably assessed and categorised in a traffic-light system ("green"- "yellow"- "red").

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Development and implementation of additional SARS-CoV-2 test capacities at the Bundeswehr Institute of Radiobiology

The SARS-CoV-2 pandemic has led to a rapidly growing demand for diagnostic tests and laboratory capacity in Germany. Therefore, a partially automated, interdisciplinary and cross-institute workflow for SARS-CoV-2 diagnostics was implemented at the Bundeswehr Institute of Radiobiology in cooperation with the Bundeswehr Institute of Microbiology.

SARS-CoV-2 has had a firm grip on the world since at least March 2020. Especially in the spring of 2020, the SARS-CoV-2 pandemic led to a rapidly growing demand for diagnostic testing and laboratory capacities in Germany. In order to counteract the feared bottleneck in diagnostic tests, the Bundeswehr Institute of Radiobiology tried to use already existing polymerase chain reaction (PCR) infrastructures for SARS-CoV-2 diagnostics. Although these existing high-performance PCR-based diagnostics had been tested and validated many times for radiobiological testing, the performance of any kind of virus diagnostics, including SARS-CoV-2, was a novelty at this point. The aim was therefore to convert the existing workflows for SARS-CoV-2 diagnostics as quickly as possible in close cooperation with the Bundeswehr Institute of Microbiology so that up to 200 additional samples per day could be tested if necessary.

The existing laboratory equipment at the Bundeswehr Institute of Radiobiology first had to be upgraded with appropriate software specifically for virus diagnostics and the necessary materials had to be procured. Within weeks, the viral diagnostic

capability could then be established and validated in several test runs, achieving a quality standard comparable to the data of the accredited test laboratory of Bundeswehr Institute of Microbiology. Particularly noteworthy was the resulting largely automated, interdisciplinary and inter-institute workflow (Figure 1) for rapid and high-throughput diagnostics of SARS-CoV-2 samples. As part of this workflow, the virus-inactivated patient samples were processed by the partially automated laboratory robotics (Figure 1B) and prepared for direct virus detection.

In the subsequent “multiplexing” quantitative real-time PCR (qRT-PCR, Figure 1C), the current gold standard of SARS-CoV-2 diagnostics, several target genes were detected simultaneously to increase the specificity and sensitivity of direct virus detection. The results of the qRT-PCR were interpreted by the specialists at the Bundeswehr Institute of Microbiology, who also made the final diagnoses (Figure 1D).

With their expertise, both institutes made vital contributions to the significant increase in test capacity in the spring of 2020 – the Bundeswehr Institute of Microbiology by ensuring virus inactivation of the patient samples and evaluating the qRT-PCR data, the Bundeswehr Institute of Radiobiology by providing partially automated RNA isolation and performing qRT-PCR.

The key to the successful, interdisciplinary and inter-institute establishment and implementation of SARS-CoV-2 diagnostics at the Bundeswehr Institute of Radiobiology was undoubtedly the smooth cooperation between the two institutes. Thanks to this cooperation and the high standards of work and performance at both institutes, SARS-CoV-2 diagnostics at the Bundeswehr Institute of Radiobiology could be established not just successfully but also quickly, i. e. in a matter of weeks rather than several months.

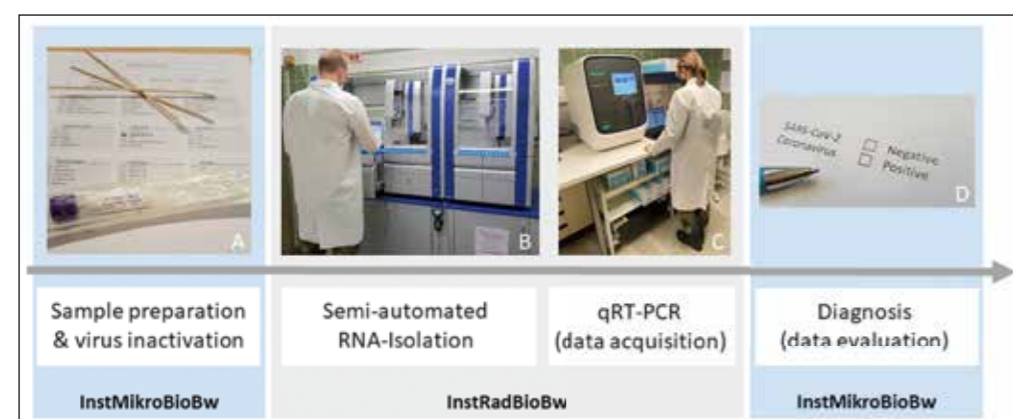


Fig. 1:
Schematic overview of the cross-institute, partially automated workflow:
A) sample processing and virus inactivation at Bundeswehr Institute of Microbiology (InstMikroBioBw);
B) semi-automated RNA isolation with the QIAGEN QIASymphony®;
C) qRT-PCR with the QuantStudio™ 12K OA Real-Time PCR System at Bundeswehr Institute of Radiobiology (InstRadBioBw);
D) interpretation of results and diagnosis at the Bundeswehr Institute of Microbiology

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Effects of the COVID-19 pandemic on anxiety, aggression and anger among hospital staff and patients

The COVID-19 pandemic was the greatest global challenge of 2020. A civil-military collaboration examined its effects on anxiety, aggression and anger among hospital staff and a high-risk population affected by COVID-19. Recommendations are derived from the results for hospital staff and the treatment of patients.

Because of its rapid spread, the congestion of health facilities and the high death rate among patients, COVID-19 was the defining global sociopolitical and health issue of 2020. The sense of physical and economic threat and the associated massive restrictions were a major challenge in terms of mental health.

The effect of the COVID-19 pandemic on anxiety, anger and aggression was examined in a civil-military cooperation. The Psychological Service of the Bundeswehr, represented by the Psychotrauma Centre of the Bundeswehr Hospital in Berlin, contributed its expertise in psychotraumatology. For civilian populations, this includes investigations into terrorism or spree killings associated with intentional incidents, traffic or aircraft accidents as well as screen analysis of extreme events in the case of work-related trauma. The civilian partner was the Clinic for Cardiology and Angiology of the West German Heart and Vascular Centre of the University of Duisburg-Essen. The clinic covers the entire range of contemporary cardiovascular medicine and is one of the world's leading providers of full-spectrum cardiovascular care. This research cooperation was the first time that psychometric data was acquired in Germany with



Fig. 1: Inpatient care and monitoring of patients with COVID-19 (source: Thilo Pulpanek; Bundeswehr Hospital Berlin; ©Wesemann et al. 2021)

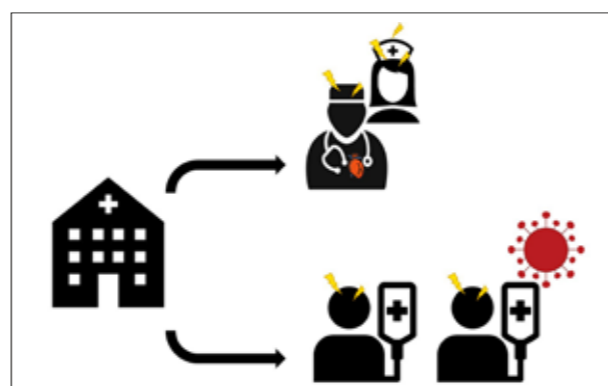


Fig. 2: Diagram of the two-armed study design with hospital staff and COVID-19 patients (Vector graphics: Vecteezy.com, graphic design: Charlyn Braun; Wehrmedizinische Monatsschrift issue 3-4/2021)

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a two-arm study design including both hospital staff and affected patients.

The first study arm included the hospital's medical staff and was able to show that direct contact with patients with COVID-19 resulted in less anxiety-specific symptoms or anger than indirect or no contact. This is attributed to the belief of respondents that they can protect themselves against infection in direct contact with patients. This locus of control can be positively influenced by the employer. Effective protective measures within the facilities and their transparent communication by management are of crucial importance.

Female staff members reported higher scores on an anger expression inventory than their male colleagues. This is explained by the double burden of family and work, which, according to the German Federal Statistical Office, women have to bear more frequently, even more so in times of lockdowns, home-schooling and closures of day-care centres and childcare facilities.

The second study arm focused on hospitalised patients with COVID-19 and concomitant severe pulmonary, cardiovascular or oncological disease. There was an increased prevalence rate (38%) of post-traumatic stress disorder (PTSD). In most studies with comparable inclusion criteria – but without COVID-19 –

the rate is below 10%. The life-threatening prior diagnoses alone constitute medical trauma. The additional factor of COVID-19 leads to a very poor medical prognosis. Anger as a stable personality trait was identified as a risk factor for PTSD in this population. Anger explained up to 25% of the variance in post-traumatic stress symptoms and is therefore of particular interest for prevention. Routine screening or psychological counselling are strongly recommended for high-risk patients so as not to overlook mental health problems.

Continuing this scientific psychocardiological collaboration will facilitate knowledge gains that can be exploited to further optimise treatment.



Fig. 3: Chest CT scan of a patient without COVID-19: the lung parenchyma is ventilated on both sides (source: Bundeswehr Hospital Berlin)

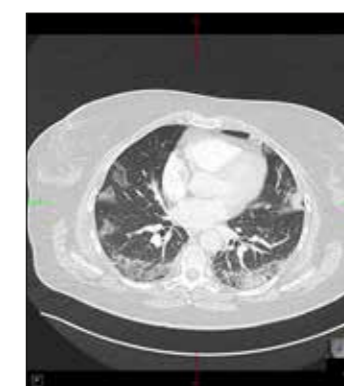


Fig. 4: Chest CT scan of a patient with COVID-19 infection: calloused indurations in the basal sections of the lungs on both sides are apparent in the lung parenchyma (source: Bundeswehr Hospital Berlin)

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Randomised controlled study on the effectiveness of equine-assisted intervention in deployment-associated mental disorders among active and former service members of the Bundeswehr

On behalf of the German Ministry of Defence, the Psychotrauma Centre of the Bundeswehr is conducting a randomised controlled study on equine-assisted therapy for post-deployment disorders among military service members to determine effectiveness and possible influencing factors. The study compares two different intervention types of horse-assisted therapy with a “treatment as usual” condition.

Since the early 1990s, more than 400,000 German soldiers have taken part in foreign missions of the Bundeswehr. Almost 90 % of them have experienced high stress levels and almost 50 % have experienced extreme and potentially traumatic events. Up to 25 % experienced mental illness after their return. Some of these soldiers report long-term problems, such as concentration disorders, irritability, avoidance behaviour, insomnia and nightmares, which can be attributed to post-traumatic stress disorder (PTSD) or other deployment-related disorders, such as adjustment disorder, anxiety, affective and somatoform disorders.

On average, however, five years pass between a German soldier experiencing a traumatic event and eventually accepting psychosocial support. Previous studies have shown that the treatment methods recommended in the relevant guidelines are less effective in military patients compared with civilian patients.

One way to compensate for this may be the use of animals in treatment. Dogs and horses in particular are increasingly



Fig. 1: Only select horses with intervention experience are used for the study (source: PIZ BAPersBw)



Fig. 2: Previously deployed soldiers work closely together with therapy horses during the six-week intervention. Trauma-specific treatment is not part of equine-assisted therapy (source: PIZ BAPersBw)

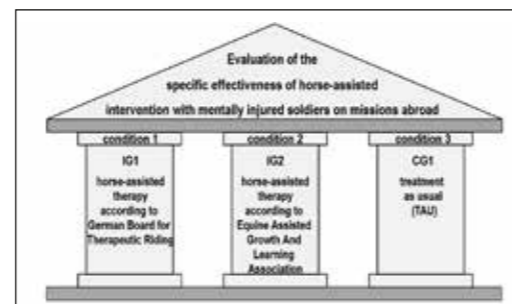


Fig. 3: The three study arms of the evaluation project (source: Dr. Kai Köhler)

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being used in interventions in social work, family counselling and as a supplement to therapy. Studies have shown that animal-assisted interventions can reduce symptoms of anxiety, trauma and depression, with improved self-confidence and social support as well as lower treatment dropout rates. A study of US veterans undergoing hippotherapy showed improvements in self-efficacy, emotional regulation, daily task completion and social and emotional loneliness.

In a first pilot study conducted by the Psychotrauma Centre of the Bundeswehr, one weekend of equine-assisted interventions (EAI) for couples was found in a pre-post comparison to lead to a reduction in PTSD symptoms (Figures 1 and 2). Because of the insufficient number and methodological quality of available studies, however, conclusive evidence-based proof of efficacy is not yet available.

That is why the Psychotrauma Centre has been tasked with conducting a randomised controlled trial (N = 200) with three study arms (Figure 3) to evaluate the therapeutic effectiveness of an EAI carried out to complement standard treatment.

The intervention will last 6 weeks (16 h of equine-assisted individual therapy) at two training sites in Berlin and Wittenberg (Figure 4). Psychometric testing, physiological measurements

(heart rate variability, skin electrical resistance) as well as cortisol level testing (saliva / hair) will be carried out before (baseline), during (at 3 + 6 weeks in) and after (at 1 week + 3 months post intervention) the intervention, with results statistically evaluated.

Any effects on the horses in terms of their stress levels (salivary cortisol, heart rate variability, video-based behavioural observation) during the intervention will also be evaluated in cooperation with the veterinarians of the Bundeswehr Medical Service (Figures 5 and 6).

The study will focus on the following research questions:

1. Can EAIs sustainably reduce negative symptoms both specific and not specific to a post-traumatic disorder and improve subjective quality of life?
2. Can changes that are due to therapy be detected in terms of physiological stress responses?
3. Do EAIs have an effect on the physiological stress parameters of the horses used in treatment?

Initial results of the evaluation should be available in 2022, a final evaluation in 2024.

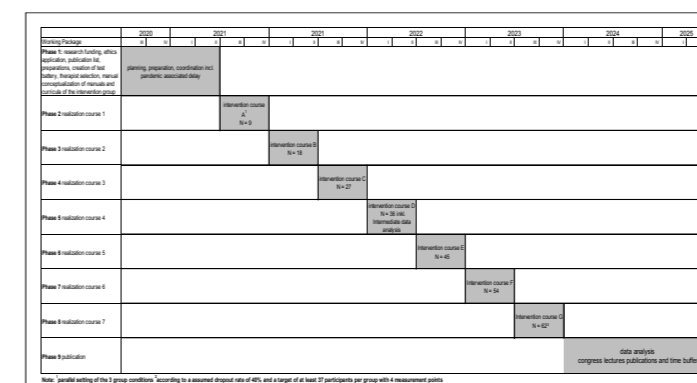


Fig. 4: Schedule and timeline of the study (source: Dr. Kai Köhler)



Fig. 5: Collecting a saliva sample for cortisol level testing (source: Frederike Wendt; Berlin)



Fig. 6: Applying an HRV measuring belt (source: Frederike Wendt; Berlin)

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Screening for functional effects of repeated hypobaric exposure in altitude chamber staff: A European multinational study

White matter hyperintensities on MRI brain scans are considered abnormal findings in people under the age of fifty. Their higher incidence in cohorts who have repeatedly experienced occupational hypobaric exposure calls into question the supposed harmlessness of such exposures. The study presented here examines the effects of such exposures on hypobaric chamber staff involved in pilot training.

White matter hyperintensities (WMH) found on magnetic resonance images (MRI) of the brain represent unspecific neuronal damage that occurs more frequently with ageing. In people below the age of fifty, however, they are considered an abnormal finding. They are associated with increased morbidity and mortality in conditions such as vascular dementia and Alzheimer's disease as well as with cognitive decline and poorer clinical outcomes. Cardiovascular risk factors (arteriosclerosis, hypertension, diabetes mellitus, elevated blood lipids, smoking, etc.) and certain activities such as diving and mountaineering further increase the likelihood of their development.

Despite extensive research in recent years, neither the pathogenesis of such changes nor their functional implications has been conclusively determined.

In the aeromedical context, the increased incidence of WMH especially in younger, regularly examined cohorts with repeated occupational exposure to non-hypoxic, hypobaric conditions (as is the case for U-2 pilots, astronauts, and altitude chamber instructors who work in pilot training) together with the results



Fig. 1: View into the altitude chamber at the German Air Force Centre for Aerospace Medicine in Königsbrück while an inside safety monitor instructs pilots in training (source: Stephan Ink, Bundeswehr)

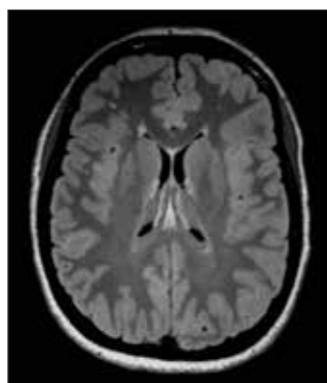


Fig. 2: T2-weighted FLAIR (fluid-attenuated inversion recovery) image with multiple white matter hyperintensities in a 3T MRI scan of a test person (source: Dez. „Bildgebende Diagnostik“, ZentrLuRMedLw)



Fig. 3: Portable TETRIX Interactive Balance System made by Neurodata for measuring balance regulation (source: Dr. Carla Ledderhos, Bundeswehr)

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of animal studies prompted a critical review of the safety of such frequent altitude exposure.

To examine the issue, a working group named “The Impact of Hypobaric Exposure on Aviators and High-Altitude Special Operations Personnel” was formed as part of the NATO Science and Technology Organisation. Within this group, the German representatives of the German Air Force Centre of Aerospace Medicine initialised a clinical study that included altitude chamber instructors from various European nations and examined the prevalence of WMH in MRI scans of the brain and the spinal cord as well as their functional implications after repeated non-hypoxic, hypobaric exposure.

For this purpose, altitude chamber instructors (Figure 1) who are regularly exposed to hypobaric conditions as part of their work are studied in comparison with a control group matched for age and gender without a personal history of such exposures (altitude chamber, diving or mountaineering). The study involves a detailed personal history as well as 3T MRI scans of the brain (Figure 2) and the spinal cord. The functional tests focus on balance regulation using posturography (Figure 3) as well as on sensory pathways with recordings of visual and auditory evoked potentials (Figure 4). Optical coherence tomography (Figure 5) is performed to image the fundus of the eye,

including the optic nerve and the retinal vessels. Psychometric tests (Figure 6) are also conducted.

A total of 49 subjects (21 chamber instructors (CI), 28 control subjects (CS)) have been studied so far. Available data of the ongoing study suggest no differences in the mean number and volume of WMH between both groups. However, 56 % of CI but only 46 % of CS had more than 5 WMH in the brain. Data obtained so far confirm a correlation between age and number as well as volume of WMH in the brain, which previous studies have also found. Most WMH (58 %) were located in the subcortical region of the frontal lobe. In both groups, the occipital lobe was free of WMH, as was the spinal cord. As far as the functional consequences of WMH are concerned, only the psychometric data show a tendency of slight differences between the groups so far.

The results of the study will allow better assessment of the occupational risk that CI face.

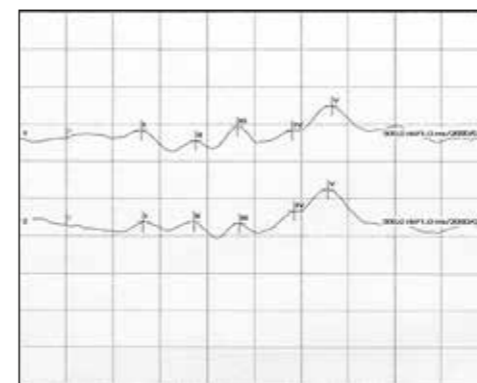


Fig. 4: Example of an auditory evoked potential for functional examination of the auditory pathway (source: Dezernat „Neurologie/Psychiatrie/Klinische Psychologie“, ZentrLuRMedLw)

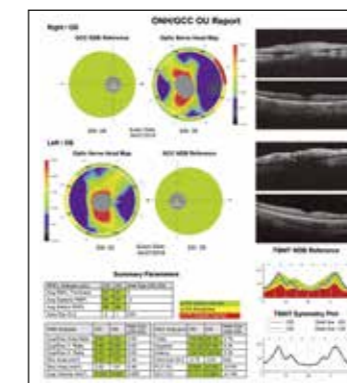


Fig. 5: Part of optical coherence tomography performed on a test person (source: Dezernat „Augenheilkunde“, ZentrLuRMedLw)

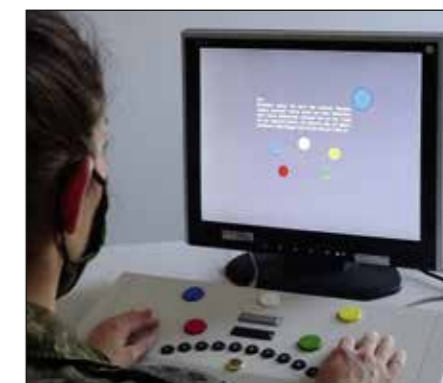


Fig. 6: Participant performing the Vienna determination test (source: Dr. Carla Ledderhos, Bundeswehr)

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Immunological changes due to hyperbaric oxygen: How does technical diving influence the immune response?

Environmental changes induce several immune reactions. Technical / military diving induces an unphysiological increase of oxygen (hyperoxia), which can lead to possible immunological reactions. Lymphocytes taken from healthy subjects displayed a cellular adaptive immune response with activation of regulatory T-cells.

Environmental factors greatly influence the human immune system. Not only acute or chronic infections, but also stress, certain foods, or even changes in sleep behaviour lead to changes in immunological homeostasis.

There is a physiological state of reduced oxygen availability (hypoxia) in certain parts of the body, such as in tissues with poorer blood circulation. Pathological changes, however, can also lead to hypoxic conditions in areas that are otherwise well supplied with blood, e.g. in patients with pulmonary oedema or local inflammation. Several studies have shown the body's ability to adapt through locally induced changes in immune cells. The so-called hypoxia-induced factor 1-alpha (HIF-1alpha) plays a central role in this process. It is activated in the cells by hypoxia and triggers a series of immunological reactions, leading to activation and proliferation of distinct T-cells. These cells aid in a more effective local reaction of the adaptive immune system. On the other hand, regulatory T-cells are also activated by HIF-1alpha, which can suppress a possibly pathological immune response.



Fig. 1: Combat swimmer of the German Navy



Fig. 2: Experimental hyperbaric chamber at the Naval Institute of Maritime Medicine

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Exposure to increased pressure during technical diving causes an unphysiological increase in oxygen partial pressure (hyperoxia), which is amplified many times over by the use of pure oxygen (Figure 1). In comparison to hypoxia, very little is known about immune reactions associated with hyperoxia. However, animal models have shown a possible immunosuppressive effect under repeated application of hyperbaric oxygen.

A current project at the German Naval Institute of Maritime Medicine focuses on the immune response of healthy subjects under hyperbaric oxygen. The different immune cells are analysed with flow cytometry before and after hyperoxia. Additionally, isolated immune cells are exposed in vitro to the same stimulus using an experimental pressure chamber (Figure 2) in order to differentiate possible migration effects. Changes in the receptor network are validated with real-time PCR.

Compared with published studies on the effects of hypoxia, the results of this study surprisingly show similar results under hyperoxia. The T-helper cells show clear activation both ex vivo and in vitro by changing their phenotype to so-called effector T-cells. In addition, these effector T-cells polarise into so-called TH1 helper cells while the proportion of TH2 helper cells is reduced (Figure 3). Similar to the effects of hypoxia, applied

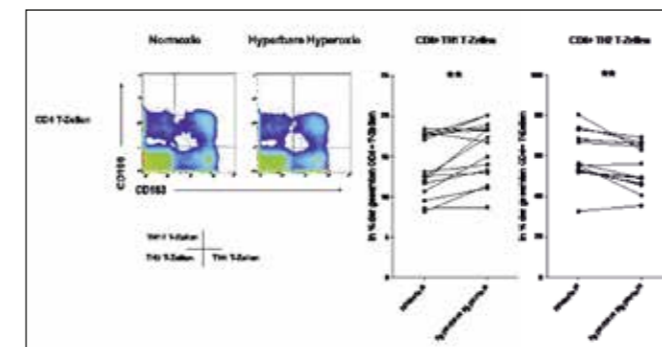


Fig. 3: Flow cytometry analysis of CD4+ T-cells of healthy subjects before and after exposure to hyperbaric hyperoxia

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hyperbaric hyperoxia also induces activation of regulatory T-cells, which could suppress an excessive and thus misdirected immune response (Figure 4).

In summary, these results suggest a dynamic equilibrium, with changes in normoxia towards either hypoxia or hyperoxia inducing a similar immune reaction.

Further studies are needed to examine the complexity of this response, particularly in terms of its functional and long-term immunological consequences.

Any findings are relevant not only for technical / military diving, but also for the use of hyperbaric oxygen to treat patients.

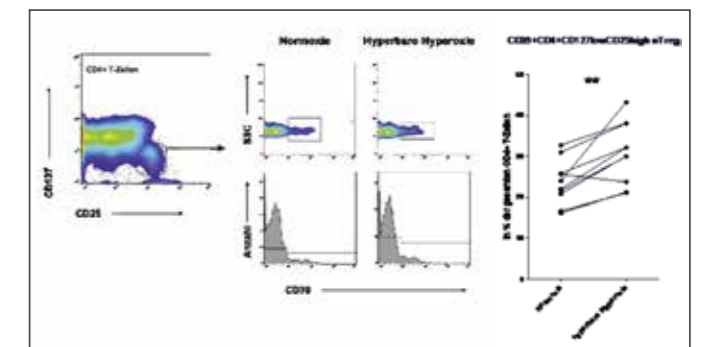


Fig. 4: Flow cytometry analysis of regulatory T-cells of healthy subjects before and after exposure to hyperbaric hyperoxia

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Using online video consultation in the Bundeswehr Medical Service

The digital transformation of the health care system leads to a significant expansion of diagnostic and therapeutic options. A special research project of the Department of Trauma Surgery and Orthopaedics of the Bundeswehr Hospital in Berlin in collaboration with the Bundeswehr Cyber Innovation Hub examined the benefits of online video consultations for the Bundeswehr Medical Service.

In the context of the digital transformation of the health care system, new applications are increasingly being developed and used to support patients and medical staff. Online video consultations (OVC) have also been given a legal basis in Germany in recent years and were already introduced before the COVID-19 pandemic. Their use brings advantages such as patients being able to see their doctor from home and thus avoiding long journeys and reducing waiting times.

The special research project 23K4-S-10 1921 at the Department of Trauma Surgery and Orthopaedics of the Bundeswehr Hospital in Berlin (Figure 1) has investigated the use of OVC at the interfaces between specialists, unit physicians and patients. The goal was to analyse how this option is received in the individual user groups and to what extent existing processes could be appropriately supplemented or improved by incorporating these technologies.

The project has been developed with various partners since 2018, chief among them the Bundeswehr Cyber Innovation Hub (Figure 2). Further close coordination took place with



Fig. 1: Coat of arms of the Bundeswehr Hospital in Berlin

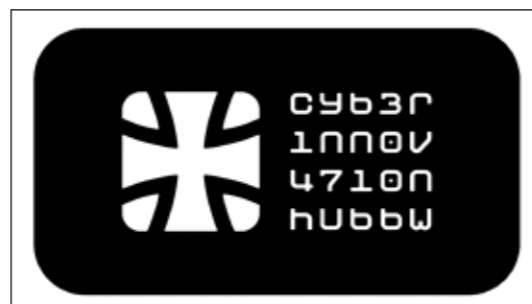


Fig. 2: Logo of the Bundeswehr Cyber Innovation Hub

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the Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support as well as with Department S6 and the Data Protection Commissioner of the Bundeswehr Hospital Berlin.

In the first part of the project, the technical and organisational establishment of the processes in the Department of Trauma Surgery and Orthopaedics of the Bundeswehr Hospital in Berlin began in August 2019 (Figure 3). Every patient who had been in contact with a specialist at the department underwent an OVC in addition to a traditional follow-up examination performed at the hospital. In addition to a user evaluation, we compared the findings made during OVCs and traditional follow-up examinations, respectively.

In the second part of the project, which began in March 2020, we evaluated the use of OVCs in speciality consults with doctors at the Department of Trauma Surgery and Orthopaedics requested by unit physicians. After every such appointment, the participating doctors and patients rated their satisfaction with the session.

Overall, the more than 120 participating patients and doctors were satisfied with the OVC process. The atmosphere in particular was rated by the majority as very pleasant. Technical and

organisational problems were easily identified and the relevant conclusions were drawn. In terms of quality, the findings made during an OVC were also often comparable with the findings established in a more traditional setting, especially in terms of recommendations for treatment. What is more, the results showed new possibilities for communication between the Bundeswehr hospital and regional medical treatment facilities, with diagnostics and treatment, supervision of conservative treatment approaches and even recommendations for surgical intervention becoming available much more quickly. Many patients and their units were spared long journeys and resources could be saved.

With these positive experiences, the project can provide a basis for the future telemedical orientation of the Bundeswehr Medical Service, especially against the background of the COVID-19 pandemic. The project could conceivably be extended to other specialist departments of the hospital or to primary care provided by unit physicians. In the medium term, similar to current plans in the civilian health care sector, the service could be expanded to include electronic prescriptions or sick notes. The use of artificial intelligence to support the evaluation of symptoms and for scheduling OVC appointments is also currently under review.



Fig. 3: Example of an online video consultation with a patient (source: Bundeswehr / Steve Back)

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Development of a bacteria-impermeable skin-metal connection for transcutaneous osseointegrated prosthetic systems

For almost 2500 years conventional amputations are provided with a socket that surrounds the stump. Over the last 15 years a treatment option has emerged, which involves an implant being inserted into the medullary canal of the residual tubular bone and passing through the skin to the outside where it is connected to the prosthesis. This transcutaneous passage creates a risk of infection for the soft tissue and bone. In collaboration with the Fraunhofer Institute for Silicate Research, a permanent physiological connection between the implant and the skin has been developed, whereby the stoma is no longer a source of infection.

In addition to the Bundeswehr Hospital in Berlin, which was one of the earliest adopters of transcutaneous osseointegrated prosthetic systems (TOPS) in Germany, at least 15 further hospitals offer this new prosthesis fitting technology worldwide. TOPS improves previous standards of residual limb care by anchoring the prosthesis directly in the femur. After sufficient osseointegration of the implant this results in direct physiological force transmission between body and prosthesis (osseoperception). In addition, skin complications caused by conventional prosthesis sockets are avoided, which limited the application of these prostheses even for young and experienced amputees. However, the TOPS technique creates a skin passage (stoma), which can always be a source of superficial or deep infection of the soft tissue (muscle, skin) or even bone. The development of a mechanically resilient and bacteria-proof connection between the implant and the skin could significantly reduce this risk of infection.

The Fraunhofer Institute for Silicate Research / Translation Center Regenerative Therapies has developed a physiological seal to close the stoma where the implant passes through the



Fig. 1: On the left, the conventional amputation stump treatment with fixation of the prosthesis using a shaft fitted around the stump; on the right, fixation by means of an implant inserted into the medullary canal of the bone, to which the same modern prosthesis system can be attached (source: Dr. Aschoff, Hannover)

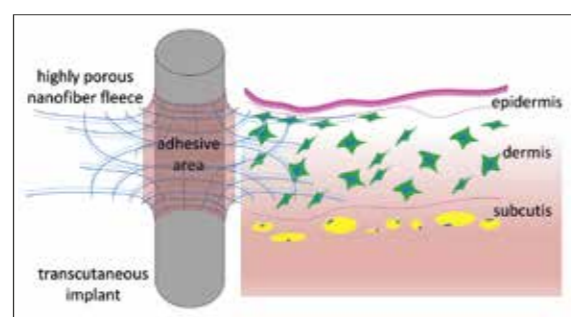


Fig. 2: The developed concept for a physiological connection of the skin with the transcutaneous implant (source: Fraunhofer ISC)



Fig. 3: Bonding of the nanofiber material to a metal cylinder representing the implant (source: Fraunhofer ISC)

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skin. This seal features a synthetic connection to the implant on one end and the most natural possible integration into the surrounding skin via a synthetic-physiological gradient. Integration of this connection into the skin requires special materials and structures, such as long-term stable materials with protein-like surface functionalities and physiologically comparable mechanical properties. In order to achieve the most natural skin integration possible, the structure of the material must also mimic the natural connective tissue of the dermis. The production of electrospun nanofibres generates structures of comparable dimensions like collagen fibres. In addition, 3D structuring processes drastically increase the porosity between these fibres. This allows cells to penetrate the fibre network and anchor the material in the dermis by building up their own environment comprising structural proteins.

Finally, the formation of an epidermis on top of the integrated fibre fleece can create a bacteria-proof and regenerative barrier. Present studies of *in-vitro* models showed a successful integration of these fleeces into skin models as well as reduced inflammatory potential. Towards the implant, the biomimetic material is bonded to the transcutaneous element. A covalent bond between the fibre material and the implant is achieved through a locally limited polymerisation reaction. Thereby, an optimal composition of the adhesive material must be found

in order to adapt its mechanical properties to this application. To achieve a long-lasting connection to the skin, a gradient of elasticity between the metal implant and the skin tissue is necessary to avoid stress peaks or weak points in this implant-skin connection.

After the successful concept development and demonstration, the individual sections and components must be fine-tuned to meet all necessary safety aspects for future clinical application.

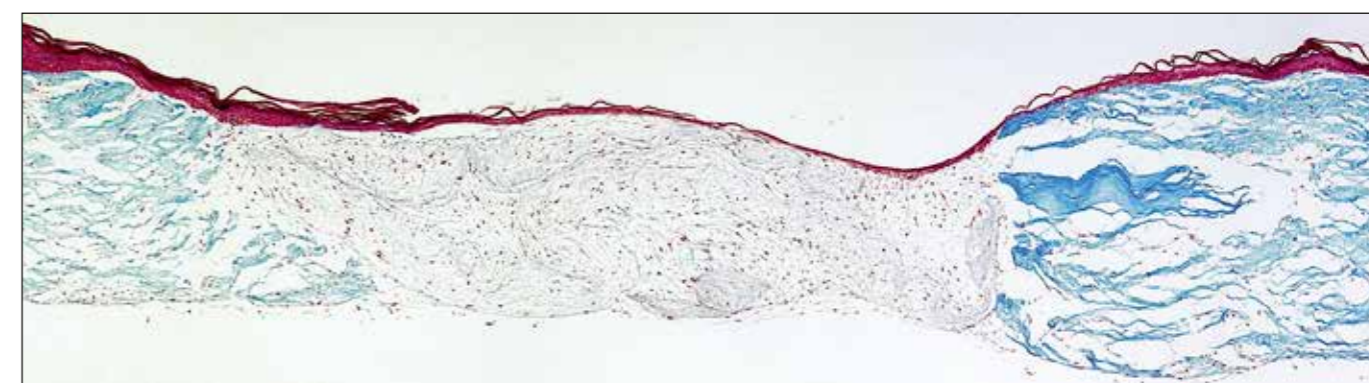


Fig. 4: In skin models, the newly developed fibrous material can be integrated into the tissue and promotes wound closure by epidermis formation (red) (source: Fraunhofer ISC)

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Assessment of simulation methods in emergency surgery training

Trauma surgeons in the Bundeswehr participate in simulation-based training in order to gain war surgery skills for deployment. The aim of this study was to assess and compare established and modern simulation modalities (SM). No SM fulfilled all requirements. Further studies must assess the value of each individual modality for use in trauma surgery training.

Military surgeons must be competent in a number of combat-specific trauma skills rarely seen in civilian practice in Germany. Training surgeons in these life-saving skills remains a major challenge for the Bundeswehr. Human cadaver (HC) and anaesthetised pig models (live tissue training, LTT) are currently used to teach emergency surgical skills. Cadaver availability is limited and live pig tissue suffers from lack of human anatomy as well as associated social pressures. Recent advances in simulator development have resulted in a number of models that may have the potential to replace or reduce the need for those currently used. This study was designed to evaluate four of the most promising human patient simulator models, with the two deemed most capable compared to the cadaveric and live tissue models.

The comparison with established SM (HC, LTT) was carried out by participants as part of the Bundeswehr Surgical Care Course for Deployed Settings. The following aspects were evaluated: feasibility and realism of emergency surgical manoeuvres with a focus on anatomy and simulated bleeding, the participants' self-efficacy as an indicator for learning success and their



Fig. 1: Placement of a temporary vascular shunt in an animal model

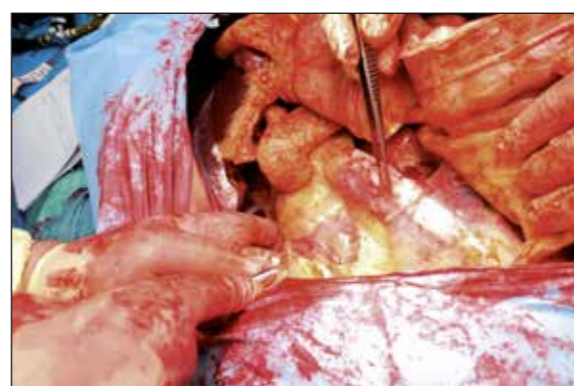


Fig. 2: Operating site of the laparotomy model produced by Strategic Operations; the attachments of the internal organs and the connective tissue are well implemented in this model. The retroperitoneal covering of the inferior vena cava and aorta as well as the Gerota's fascia are clearly visible

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stress experience. Four state-of-the-art technical human patient simulators (HPS) were evaluated by instructors of the Bundeswehr emergency war surgery course and an international panel of experts. Each simulator was evaluated (using a numerical rating scale) in the following areas: (1) practical operability and physical reality of surgical access routes, (2) identifiability and physical reality of defined anatomical key structures in the thorax and abdomen, (3) practical operability and physical reality of defined emergency surgical manoeuvres in the thorax and abdomen, and (4) characteristics in haptic palpation and dissection behaviour of different types of tissue (skin, adipose, muscle, and vascular tissues).

The two simulators deemed most capable (Operative Experience / OE, and Strategic Operations / SO) were then compared to fresh frozen HC and LTT. Sixteen participants of the Bundeswehr Surgical Care Course for Deployed Settings were surveyed about practical operability and fidelity of the different training modalities using numerical rating scales. In addition, every participant was assessed on their performance of one standardised surgical procedure on every training modality to determine increases in confidence and perceived self-efficacy. Participants were also asked to rate differences between the models in terms of (1) subjective stress perception and quality of stress, (2) mental and physical fatigue, (3) feeling overwhelmed, (4) monotony, (5) increase in knowledge and expertise, (6) focus and concentration,

(7) knowledge networking, and (8) confidence in own abilities. HPS do not yet provide the necessary level of complexity due to deficits in both anatomical realism and simulated bleeding in combination with high costs in the short and long term. While the anatomy of HC is realistic, the lack of bleeding limits their use to training technical skills in low-stress situations. LTT offers realistic tissue quality and bleeding simulation, but human and porcine anatomy differ considerably. The ethical concerns associated with LTT further limit its use. Perfused human cadavers (PHC) combine the correct human anatomy of HC with the realistic bleeding of LTT. The participants' self-efficacy showed a statistically significant increase through participation in the Surgical Care Course for Deployed Settings, although the individual impact of each SM could not be assessed. Subjective learning success was greatest when working with LTT. The psychological stress associated with working with perfused SM was greater than with non-perfused (LTT > HPS > HC).

No single model met all of the desired requirements. Each of the models tested were found to be suitable for training some but not all aspects of damage control procedures. HPS can possibly be used as part of basic training or team training. From a didactic point of view, neither HC nor LTT can currently be replaced, but integration of PHC into the Surgical Care Course for Deployed Settings seems beneficial.



Fig. 3: Perfused human cadaver; extracorporeal perfusion system of the Keck School of Medicine at the University of Southern California as part of the Bundeswehr emergency war surgery training in Wendisch Rietz



Fig. 4: Bleeding common femoral artery in the perfused cadaver model

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Detection of autoantibodies as a risk factor for severe illness and long-term sequelae after SARS-CoV-2 infection

The mechanisms behind respiratory failure and risk factors for long-term impairment of lung function in COVID-19 patients are still unclear. In a prospective study, a team of scientists at the Bundeswehr Hospital in Ulm was able to show that the production of autoantibodies may play a central role in both acute disease progression and the development of long-term sequelae following SARS-CoV-2 infection.

Some COVID-19 patients rapidly develop respiratory failure with a mortality of up to 1%. Despite the great global efforts to develop a better understanding of the disease, the pathophysiology and possible risk factors of such a development are still not fully understood.

From the very beginning of the pandemic, the Bundeswehr Hospital in Ulm was involved in the treatment of COVID-19 patients. As part of a prospective and multidisciplinary research project set up immediately upon arrival of the first patients, we collected clinical, serological and imaging data to identify possible risk factors for a severe progression of COVID-19. We also took transbronchial biopsies and performed autopsies of COVID-19 patients. This approach led to the Bundeswehr Hospital in Ulm being recognised as a participating centre of the German registry of COVID-19 autopsies.

In our study, we identified remarkable similarities between acute respiratory distress syndrome (ARDS) in severe COVID-19 and acute exacerbation of connective tissue disease-associated interstitial lung disease (CTD-ILD). Membrane-like hyaline

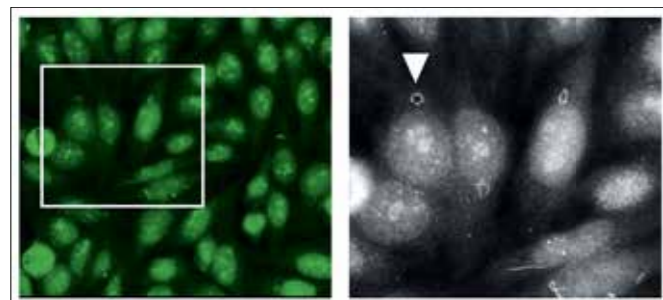


Fig. 1: Immunofluorescence-based detection of autoantibodies in a COVID-19 patient shows a finely granular and nucleolar staining pattern with rings and rods (arrow)

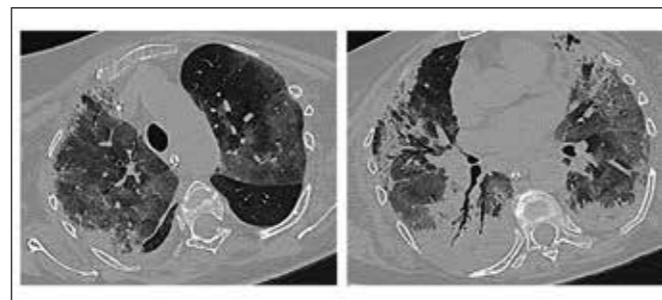


Fig. 2: Computed tomography of a 69-year-old patient with severe COVID-19 and confirmed presence of autoantibodies (1:1,000) shows diffuse ground-glass opacities along with subpleural and peribronchial consolidations with positive air bronchogram

deposits in lung alveoli (diffuse alveolar damage) as well as early deposition of collagen fibrils in the lung hinder gas exchange and can be identified on lung CT imaging as “ground glass opacities” and consolidations. Increasing amounts of interstitial collagen gradually reduce the elasticity of lung tissue and further contribute to respiratory failure. Autoantibodies (antinuclear antibodies and/or positive extractable nuclear antigens) were detected in 11 out of 13 (84.6%) COVID-19 patients with ARDS but in only 1 out of 9 (11.1%) COVID-19 patients without ARDS ($p = 0.002$). The detection of autoantibodies was significantly associated with both a need for intensive care treatment (83.3 vs. 10%; $p = 0.002$) and severe complications (75 vs. 20%, $p = 0.03$). In most cases, the identified autoantibodies belonged to the spectrum of fibrosing CTDs such as systemic sclerosis. These results were published in *Frontiers in Immunology* in October 2020.

These results have since been confirmed by independent research groups in the US, in Greece and in Japan. It has been postulated that extrafollicular B-cell activation upon SARS-CoV-2-induced activation of toll-like receptors could lead to a dysregulated immune response with secretion of autoreactive antibodies. This mechanism would also explain the effectiveness of corticosteroids in severe cases of COVID-19. Since CTD patients with a comparable serological profile can progress to lung fibrosis, it is possible that we will observe a similar course in a subgroup of young and healthy individuals after exposure to SARS-CoV-2. Based on these remarkable results, we strongly recommend assessment by a pulmonologist for military personnel with impaired lung function after COVID-19.

We have already initiated follow-up studies investigating the role of autoimmunity in COVID-19 at the Bundeswehr Hospital

in Ulm and together with collaborators in Germany and abroad. Through our involvement in the German registry of COVID-19 autopsies and another nation-wide registry for pandemics, the Bundeswehr Hospital Ulm will take a lead role in tissue-based research on pandemics throughout and beyond the armed forces. Our focus on and experience with neoplastic and non-neoplastic lung disease in patient care provides a valuable basis for current and future research with respect to infectious diseases involving the lungs.

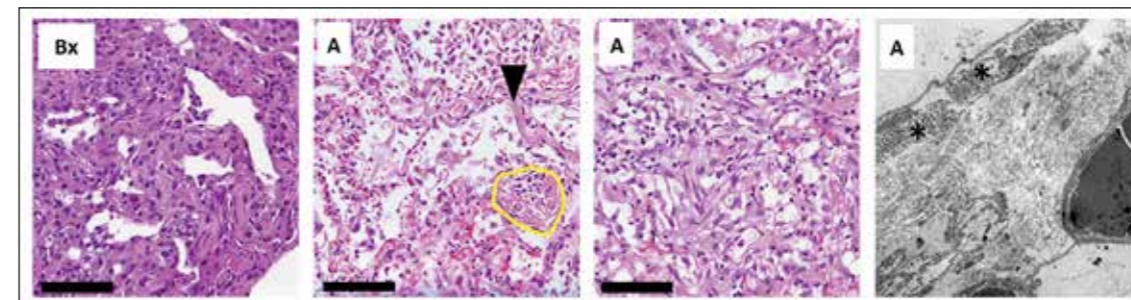


Fig. 3: Histopathological and ultrastructural assessment of tissue from a patient who died of COVID-19: a transbronchial biopsy sample (“Bx”, left) taken from a 69-year-old woman (autoantibodies 1:1,000; Figure 2 shows imaging results) 13 days after admission shows septal thickening and reactive epithelial changes. Tissue samples from the autopsy (“A”) of the same patient show diffuse alveolar damage (arrow) and alveoli with plug-like fibromyxoid organisation (yellow circle). Electron microscopy shows widening of alveolar septa with activated fibroblasts (asterisk) and deposition of collagen (silvery filaments in inter-alveolar septum).

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Evaluation of molecular diagnostic tests for tropical parasitic diseases

Infections with unicellular or multicellular parasites are a common occurrence in soldiers returning from tours of duty in tropical countries. Standardised, operator-independent molecular diagnostic tests can help deliver an early diagnosis of such infections and ensure they are treated appropriately without delay. For this reason, it is important to evaluate commercially available diagnostic tests for this purpose.

The evaluation and medical assessment of operator-independent molecular diagnostic tests for tropical parasitic diseases is the subject of a research project being carried out from 2019 to 2022 by the Bundeswehr Hospital in Hamburg at its branch office at the Bernhard Nocht Institute for Tropical Medicine, which is the National Reference Centre for Tropical Pathogens. The project is being conducted in close cooperation with civilian scientists.

Diseases caused by tropical parasites represent a health risk for troops deployed in tropical countries. German military personnel have repeatedly been diagnosed with malaria, intestinal parasites and, less frequently, with systemic parasitic diseases. Frequently detected pathogens include *Giardia lamblia* (Figure 1), which cause an infection of the digestive tract, as well as *Schistosoma* (Figure. 2), which cause schistosomiasis, an infection with worms living inside blood vessels.

In May 2018, cooperation talks took place at the Laveran Military Hospital in Marseille (Figure 3), where the tropical medicine and microbiological diagnostic assets are comparable to those of the

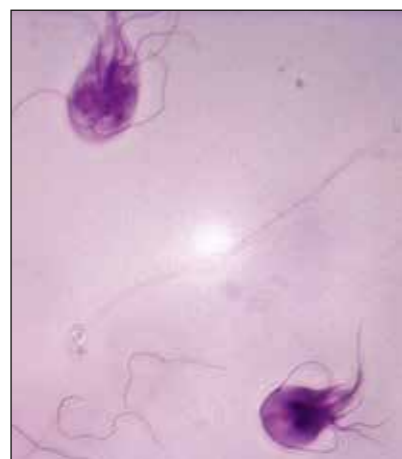


Fig. 1:
Giardia duodenalis

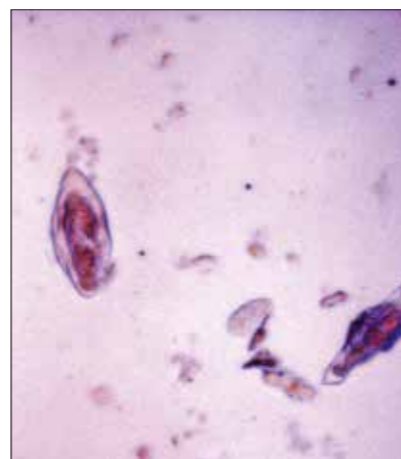


Fig. 2:
Schistosoma egg

Bundeswehr Hospital in Hamburg. These talks revealed that tropical parasitic diseases are a similarly significant issue for the French armed forces.

One issue highlighted during these talks was the lack of standardisation of molecular diagnostic tests for the diagnosis and surveillance of tropical parasites, in particular polymerase chain reaction (PCR). This makes reliable risk stratification through analysis of large quantities of samples difficult to achieve.

The establishment and evaluation of molecular diagnostic platforms for detecting tropical parasitic diseases will lay the foundations for ensuring both the diagnosis of parasitic infection in individual soldiers and the surveillance of parasites in areas of deployment.

With the exception of malaria and a few others, tropical parasitic diseases are rarely imported from the tropics and usually do not present as an emergency, which is why industry has only limited interest in expensive evaluations of tests for commercial purposes. Good multicentric evaluation studies of commercial systems are also rare. As a result, the evaluation of molecular diagnostic tests for tropical parasitic diseases remains the domain of military medical research and development.

We used anonymised residual material from diagnostic blood samples and stool samples from the participating institutions, especially from the Bundeswehr Hospital in Hamburg and the Bernhard Nocht Institute for Tropical Medicine in Hamburg to evaluate tests in accordance with ethical approval guidelines.



Fig. 3: The Laveran Military Hospital in Marseille, a partner of the Bundeswehr Hospital in Hamburg

We found satisfactory to good conformity between in-house and commercial molecular diagnostic platforms, both for blood parasites such as *Plasmodium* and for intestinal protozoans (single-celled parasites) and worms. In particular, we were able to verify a high level of diagnostic reliability for every examined molecular platform for diagnosing malaria, two of which are already being used to diagnose tropical diseases at the Bundeswehr Hospital in Hamburg. With respect to the PCR systems we examined, we also found good to very good conformity between the results of in-house and commercial testing systems. With this evaluation, we were able to take an important step towards fulfilling the requirements of EU Directive 2017/746 and the transition of tropical medicine diagnostic platforms to commercially available testing systems in 2022.

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Clinical evaluation and implementation of a high-throughput test for the detection of SARS-CoV-2 infections

The Bundeswehr Central Hospital in Koblenz and the University Hospital Bonn are collaborating in a clinical trial and in the implementation of the mass testing LAMP-seq technology for the detection of SARS-CoV-2 infections. This new technology could contribute to an urgently needed increase in testing capacity for SARS-CoV-2 infections in Germany.

In order to prevent the further spread of SARS-CoV-2 infections, reliable identification and subsequent isolation of infected persons are vital. A valid test system for large-scale screening is needed for this purpose. However, the methods currently used for diagnosing SARS-CoV-2 are limited in throughput due to technical reasons. In addition, the rapidly growing demand for diagnostic assays will deplete available supplies of the required testing material, and the high number of tests to be processed will lead to delayed test results.

A civil-military collaboration between the Bundeswehr Central Hospital Koblenz and the University Hospital Bonn has been initiated in order to both increase the test capacity and establish a highly sensitive diagnostic assay. As part of this collaboration, the LAMP-seq technology for detecting SARS-CoV-2 is being evaluated in a clinical trial.

The LAMP-seq method is based on next-generation sequencing, which is a highly scalable state-of-the-art molecular technology. Using unique molecular barcode combinations for every sample enables the simultaneous testing of thousands of samples as



Fig. 1: Swab specimen for routine diagnostics (source: Bundeswehr/Michael Laymann)

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well as reliable identification of individual positive samples in the pool.

The LAMP-seq method was pre-validated in cooperation with the Massachusetts Institute of Technology and was found to be almost entirely consistent with the results obtained by the current gold standard in SARS-CoV-2 diagnostics (RT-qPCR).

The two main limiting factors that inhibit upscaling of the currently used qPCR method – the extraction of viral RNA and the need to run individual samples for a qPCR reaction – do not affect LAMP seq. Personnel and logistical resource requirements are also reduced compared to the current gold standard method.

Every patient admitted to the Bundeswehr Central Hospital in Koblenz is routinely swabbed for SARS-CoV-2 testing (Figure 1). The collected samples are analysed using RT-qPCR (Figure 2), which is the current standard method. If the patient agrees, these samples are anonymised in compliance with data protection regulations at the Bundeswehr Central Hospital in Koblenz and used for the evaluation of LAMP-seq at the University Hospital Bonn. Finally, the sensitivity and specificity of both methods are compared for evaluation purposes.

The objective of the clinical trial and evaluation is the integration of LAMP-seq as a new, rapid and reliable diagnostic method at the Department of Microbiology and Hygiene of the Bundeswehr Central Hospital Koblenz. The cooperation partners intend to achieve (preliminary) licensing of the LAMP-seq method by the Robert Koch Institute / Paul Ehrlich Institute.

Further development of this pathogen-specific method may offer great opportunities for investigating chains of infection in outbreak situations. In addition, pathogen-specific LAMP-seq will also be a valuable tool for differential diagnosis. A medium-term goal is the development of a LAMP-seq method for use on a small and mobile sequencing platform for RDOIT public health missions (RDOIT: Rapidly Deployable Outbreak Investigation Team).



Fig. 2: Analysis of a sample for diagnosing SARS-CoV-2 infection using RT-qPCR (source: Bundeswehr/Michael Laymann)

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 military and security issues 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, 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 analyse and interpret 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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The Afghanistan operation from a historic perspective: A new research project of the Bundeswehr Centre of Military History and Social Sciences

The Afghanistan operation has become paradigmatic of Bundeswehr operations abroad, which continue to be an important element of the mission of the Bundeswehr. That is why the Bundeswehr Centre of Military History and Social Sciences will focus its future research efforts on analysing the operation. An agreement signed on 27 October 2020 now facilitates access to documents for research pertaining to this operation.

The Afghanistan operation of the Bundeswehr is of particular importance in many respects. Politically, it is a milestone of German security policy. Few, if any, other Bundeswehr operations involved as much personnel and cost as much money, saw such intense combat, claimed as many casualties, and presented such challenges for the German government and armed forces. The lessons learned in Afghanistan shaped the response to new threats and inspired ideas for ways of ensuring crisis prevention, peace and security in the future. In military terms, the Afghanistan operation is thus not just an example of Bundeswehr operations abroad but also bears paradigmatic significance.

The study of this operation will therefore be a future focus of research at the Bundeswehr Centre of Military History and Social Sciences. The interconnection of modern military history and social sciences considerably expands the range of possibilities. Important milestones achieved so far were a workshop at the Military Division of the Federal Archives in June 2019 with the aim of already using the archival material and records available there during the 30-year term of restricted access, as well



Fig. 1: Training in the field



Fig. 2: International Afghanistan workshop in 2019

as the approval of the project on 15 November 2019 by the Academic Advisory Board of the Federal Ministry of Defence for ZMSBw.

Networking with institutes and agencies in Germany and abroad as well as with research organisations and universities is of vital importance to the Centre for its own research. This is particularly true for a project such as this one. In late November 2019, the Centre thus hosted an international workshop organised in cooperation with the Netherlands Institute for Military History and attended by researchers from 14 different nations and organisations.

Without archival sources, especially without Bundeswehr records, it is almost impossible to study the Afghanistan operation – the Bundeswehr would remain a “black box”, a large unknown entity. That is why the Bundeswehr Joint Forces Operations Command has concluded a cooperation agreement with the Bundeswehr Centre of Military History and Social Sciences, granting the latter’s researchers access to the former’s records. With an initial focus on the ISAF operation from 2001 to 2014, the project team will use these newly accessible records in connection with sources from the Military Division of the Federal Archives to reconstruct and analyse this operation. This agreement thus underlines the importance of cooperation with other institutes and agencies within the Bundeswehr.

As with all publications of the Bundeswehr Centre of Military History and Social Sciences, the relevance of the Afghanistan project extends beyond just the academic community. It also contributes to civic and public education and discussion. As operations abroad will remain an important task of the Bundes-



Fig. 3: Signing of the cooperation agreement

wehr for the foreseeable future, discussions about them will continue too. The extent and nature of future contributions to these international operations and Germany’s role in them will also be discussed.

At the same time, this research is indispensable for the Bundeswehr. For one thing, it explores the bottom-up perspective, which includes tactical as well as operational aspects – in short: the military perspective. When it came to the Afghanistan operation, this was what shaped the perception among the general public. Secondly, the operation also changed the Bundeswehr itself in many respects: not just in terms of equipment, training and tactics but also with regard to its culture. Such topics will also be explored in the project, as will questions about the significance of the Afghanistan experience for the traditions of the Bundeswehr.

The multi-year research project will comprise five volumes featuring articles from various authors and will cover the overarching narrative of the Afghanistan operations from 2001 to 2014 in its various dimensions and facets, on both the international and national levels.

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Taboo and tolerance: How the Bundeswehr dealt with homosexuality from 1955 to the turn of the millennium

Commissioned by the German Federal Ministry of Defence, this study is the first of its kind to scientifically examine how the Bundeswehr dealt with homosexual service members. Until the turn of the millennium, homosexuality was considered both a criterion for exclusion from a career as an officer or non-commissioned officer (NCO) and a security risk.

The study is based on the surprisingly extensive records in the Military Division of the German Federal Archives, a large number of verdicts of the Bundeswehr disciplinary and complaints courts as well as administrative courts, and the testimony of more than 60 contemporary witnesses. These witnesses include not only former and active service members who are themselves homosexual but also service members who witnessed the treatment of homosexual fellow service members as well as former decision-makers in the armed forces and the Ministry: politicians, civil servants, generals and officers, as well as former members of the German Military Counterintelligence Service. The study examines important issues concerning the history of homosexual service members in the Bundeswehr, including questions about legal action taken against homosexual men pursuant to the infamous Paragraph 175 of the German Criminal Code (until 1969), about disciplinary action within the Bundeswehr, about career-related legal consequences of reported homosexuality, and about the assessment of homosexuality as a security risk at that time.



Fig. 1: Private Dierk Koch, a temporary-career volunteer, was instantly dismissed from the German Navy in 1964 pursuant to Section 55 (5) of the Legal Status of Military Personnel Act (Soldatengesetz) when he was outed as homosexual

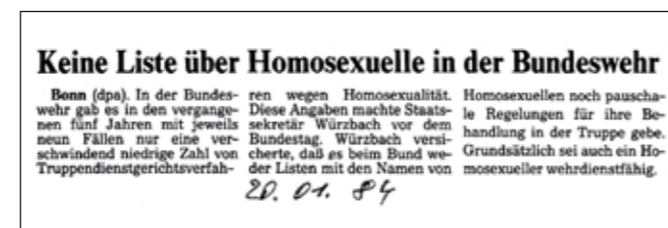


Fig. 2: As a result of the scandal surrounding the dismissal of General Günther Kiessling in January 1984, media interest also focused on how the Bundeswehr dealt with service members who, unlike Kiessling, were actually homosexual. The German Federal Ministry of Defence was forced to deny keeping lists of these soldiers

Until 1979, men who outed themselves or were perceived as homosexual during the recruitment process were systematically excluded from military service. After 1979, homosexuality no longer rendered a man unfit for service; instead, the prevailing principle was that, while compulsory military service was possible, a career in the military was not. Contemporary witnesses interviewed by the author of the study vividly and credibly recount the intense psychological pressure under which homosexual NCOs and officers served. On the other hand, many contemporary witnesses also confirmed that tolerance among the troops was actually much greater than the regulations allowed. According to these regulations, men who had been outed as homosexual were universally unsuitable for positions as superiors or instructors – a blanket ban that expressly did not take individual factors into consideration. The deciding factor was a presumed loss of authority and thus the assumption that discipline among the troops would be at risk. The Bundeswehr refused any extension of the period of enlistment and blocked all attempts to become a career service member in all cases and irrespective of previous performance. Until 1990, all attempts to ease these restrictions through the administrative courts ended in failure.

Furthermore, homosexuality was considered a security risk. New guidelines in 1988 only considered officers and NCOs potentially susceptible to blackmail if they kept their homosexuality a secret in their professional life. But potentially career-damaging restrictions remained in place, making it almost impossible for anyone to come out. During the infamous Kiessling affair in January 1984, the German weekly Die Zeit got to the heart of this conflict: “It was this very discrimination that created the susceptibility to blackmail” and “the Bundes-

wehr created its own security risks”. A way out of this “dilemma”, acknowledged as such by the Ministry in January 2000, was only possible if the Bundeswehr changed its attitude towards homosexuality. After years of waiting and calling for change, that step was finally taken in 2000 with a decision by then Minister of Defence Rudolf Scharping – against the fierce resistance of military leaders.



Fig. 3: In the 1990s, the Nationwide Association of Gay Service Members (Bundesweiter Arbeitskreis schwuler Soldaten (BASS)), supported by the Gay Men's Federation in Germany (Schwulenverband in Deutschland (SVD)), demanded the removal of all restrictions on openly gay officers and non-commissioned officers in the Bundeswehr

4

Geoscientific Research

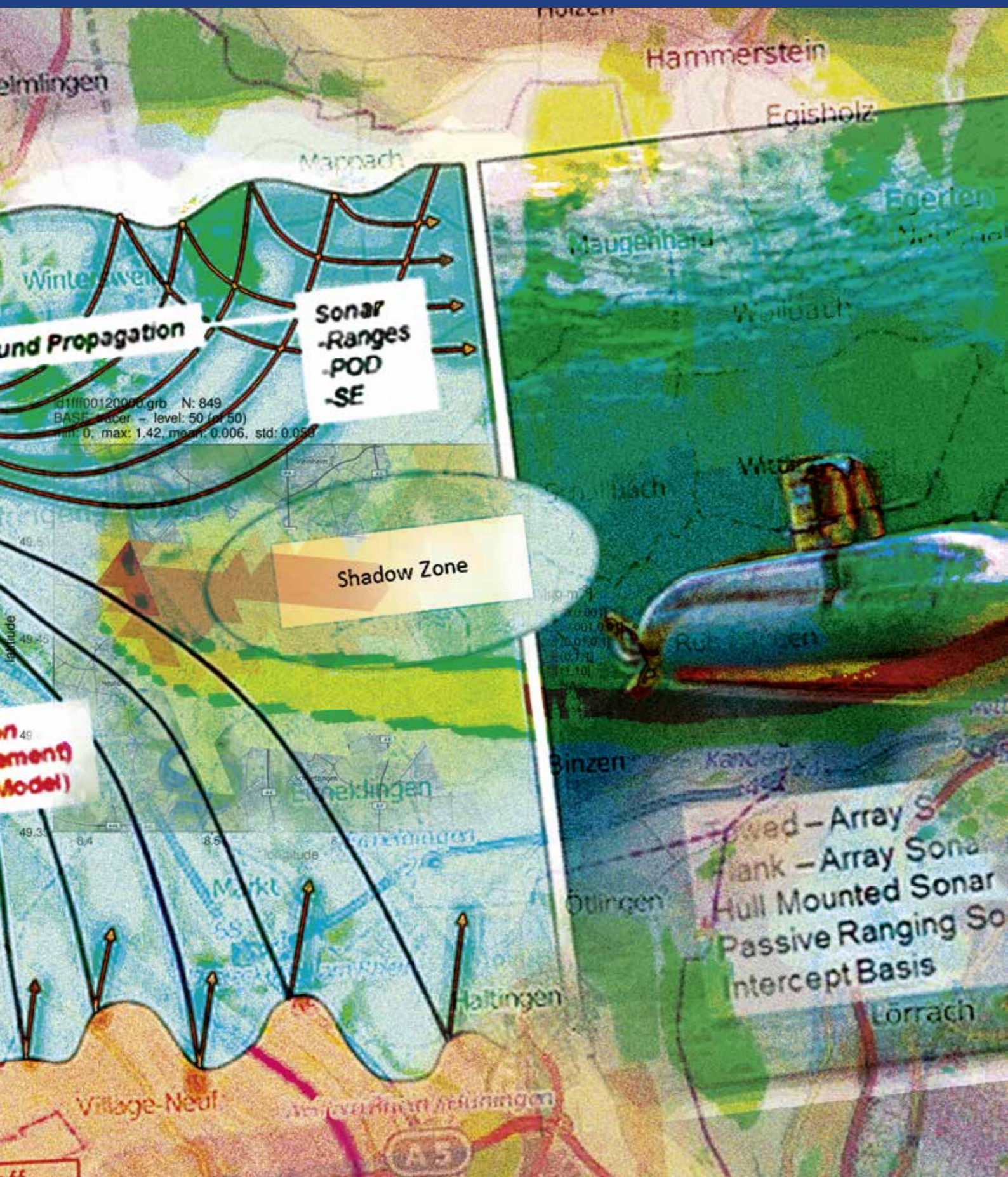
Geospatial factors refer to all natural and anthropogenic features of the environment (such as climate, weather, terrain, bodies of water, vegetation, infrastructure, etc.) that are relevant for military capabilities and military operations. The challenging and diverse tasks of the Bundeswehr fuel an increasing demand for reliable information on the spatiotemporal variability of geospatial factors. This is true for international crisis management operations, national and collective defence, humanitarian emergency aid, and disaster relief operations.

Applied geoscientific research is carried out in the area of responsibility of the Federal Ministry of Defence in order to place geoscientific developments at the disposal of the Bundeswehr and to find new and appropriate geoscientific methods and procedures. The Bundeswehr Geoinformation Centre is the central agency of the Bundeswehr Geoinformation Service and is in charge of this research. The Centre is organised according to processes. The Applied Geosciences directorate is responsible for research activities. In accordance with the add-on principle, research and development (R&D) activities are initiated and carried out whenever R&D requirements cannot be met by external academic and research institutions and when required by national security interests. R&D activities are conducted as geoinformation projects using Bundeswehr personnel and funds, by external contractors, or as a combination of the two approaches. A scientific advisory council consisting of national and international experts offers technical support to the Centre.

Long-term priorities in geoscientific research include big data analytics, artificial intelligence, virtual and augmented reality,

geoinformation data management, the quality of online services, and positioning, navigation and timing. Geoscientific research covers a wide variety of disciplines and must be able to respond to short-term changes in requests for geoinformation support. This calls for flexibility and the capacity to deal with issues outside one's primary field on an ad hoc basis.

The following two examples of geoscientific research show the diversity and complexity of R&D activities at the Bundeswehr Geoinformation Centre.



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Further development of a regional oceanographic model

The geoinformation branch of the German Navy Headquarters helps the Navy plan and conduct exercises and operations around the world. Such missions require an operational oceanographic model for forecasting ocean currents and water column stratification. Present and future conditions at sea are computed based on hydrodynamic numerical model simulation.

New acoustic sensor systems such as flank and towed array sonars are associated with increased accuracy and the spatial and temporal resolution of the oceanographic forecast in the three-dimensional theatre of operations. Modelling of vertical stratification conditions serves to predict hydroacoustic conditions for submarines, to provide input data for tactical planning aids, and to facilitate acoustic underwater communication. It is used in mission planning for underwater equipment and divers as well as in the forecasting of currents, in particular surface drift forecasting.

The survival of a person in water depends on water temperature and, above all, on search and rescue (SAR) times. Knowledge and precise forecasting of the drift caused by ocean currents can crucially shorten these times. Security authorities too are interested in maritime currents, for example in order to track refugee and migration movements across the Mediterranean Sea and to curb human trafficking. In many cases, people in overcrowded and open boats drift with ocean currents for days. Knowledge of currents allows authorities to locate the place of departure and to calculate the estimated target.

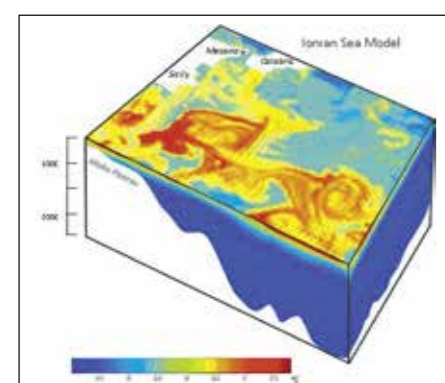


Fig. 1: 3D ocean (source: U. Paul, MarKdo)

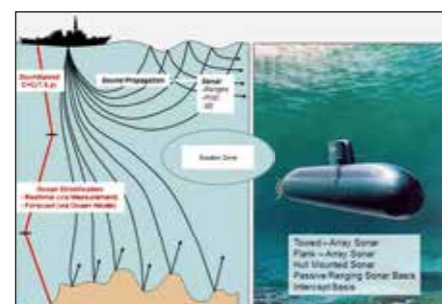


Fig. 2: A submarine in the model ocean (source: Marine, www.die-marine.de)



Fig. 3: The new high-performance computer at the German Meteorological Computing Centre (source: DWD NEC TWL-KOM RZ II Ludwigshafen)

For submarines and antisubmarine warfare, knowledge and prediction of the vertical stratification of the water column is of particular interest because this information can be used to identify sonar propagation conditions. Likewise, sound velocity fields are used to compute detection probabilities in mine hunting. Seawater density can also be forecast for all maritime areas as it changes with temperature, salt content, and pressure. Knowledge of density is necessary, for instance, for determining the trim of underwater equipment.

In order to assess risks from underwater sound, hydroacoustic forecasts are produced which are based on ocean stratification, among other things. Risk maps are created for this purpose which indicate areas where there may be hazards for aquatic life as a result of active sonar or underwater demolitions.

These forecasts are based on ocean simulations that are calculated by routine hydrodynamic numerical ocean modelling on a high-performance computer at the German Meteorological Computing Centre. Currently, eight maritime areas are routinely simulated at the Centre: the Ionian Sea, the Strait of Gibraltar, the eastern Mediterranean Sea, the western Black Sea, the Gulf of Aden, the east coast of Somalia, the central Mediterranean Sea, and the Strait of Hormuz. Figure 1 shows the calculated temperature distribution for the Ionian Sea. Other parameters such as ocean currents, salt content, sound velocity, density, and sonar conditions can also be shown.

The further development of the regional oceanographic model is designed to improve the efficiency and quality of forecasts. The future model is to be supplied in real-time with current data from the ICON (Icosahedral Nonhydrostatic) meteorologi-

cal model of the German Meteorological Service with coupled surface conditions. Lateral oceanographic conditions are fed in from the European MERCATOR global model. In addition, the global ocean model project will ensure this supply of boundary values to regional ocean models in a fail-safe and prompt manner.

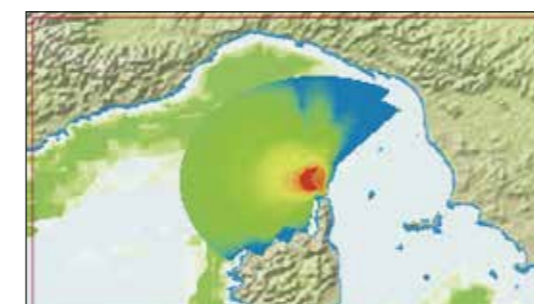


Fig. 4: Risk map for underwater sound (source: NATO)



Fig. 5: Search and rescue area. High-quality ocean current forecasts significantly reduce search times (here more than 53 %) (source: German Navy, SAR Headquarters)

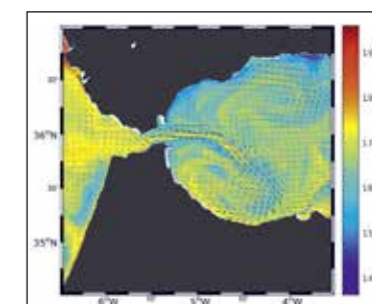


Fig. 6: Strong inflow into the Strait of Gibraltar (source: MarKdo)

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HEARTS and pollutant dispersion modelling at the Bundeswehr Geoinformation Centre

Dispersion modelling of pollutants is an important aspect of meteorological advice provided by the Bundeswehr Geoinformation Centre for both military and civilian operations. Research in this field focuses on improving existing procedures as well as developing scientifically more complex approaches.

HEARTS (Hazard Estimation for Atmospheric Release of Toxic Substances) is a consulting tool that was developed at the Centre and that supports military and civilian organisations in a variety of ways. HEARTS uses forecasts of wind and stability conditions in the atmospheric boundary layer. This information comes from numerical weather predictions of the German Weather Service. A consulting product is generated from the weather information and the special properties of the material (chemical, biological, nuclear) for which a forecast is to be made (Figure 1). In order to make timely decisions on site after an event so that effects are as limited as possible, HEARTS uses time-critical calculations. The ability of the user to act and control the situation is significantly influenced by this.

HEARTS is a Gaussian puff model, which advects Gaussian clouds in the horizontal plane. Its advantages are that it is a fast and accurate method with a user-specific graphical interface (Figure 2). Its advantages of a fast and accurate method with a user-specific graphical interface (see Fig. 2) are counterbalanced by disadvantages: no vertical advection, no subscale orography and low temporal resolution (1h) of the weather information.

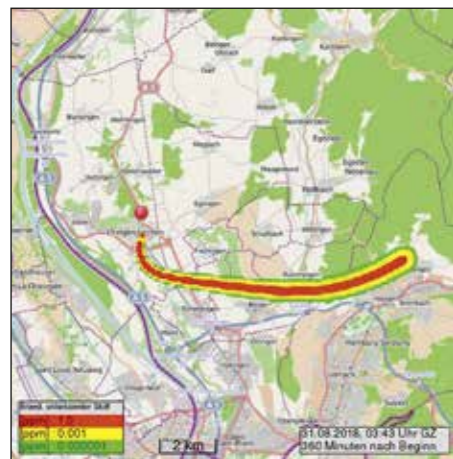


Fig. 1: HEARTS dispersion calculation; number concentration (ppm) of an unknown substance (6 h forecast) (source: ZGeoBw III 4 (2))



Fig. 2: HEARTS user-specific graphical interface; here for users of "Weather forecast control centre at the German Weather Service" and "Meteorological forecast centre at the Centre" (source: ZGeoBw III 4 (2))

In the scientific context of pollutant dispersion modelling, this method is no longer state-of-the-art. For this reason, research by the Centre and the German Weather Service in 2020 focused on investigating and adapting more advanced methods. A Lagrangian particle dispersion model, which was developed and is being further evolved in the DWD, would be suitable for the short range (< 50 km) and fast availability (< 30 min). Initial tests on the NEC high-performance computer, which went active in 2020, suggest that this method is fast enough for time-critical operations. Here in particular, the integration of pollutants is a current focus of research.

The "counterpart" to Lagrangian modelling is Eulerian modelling, in which wind field and pollutant concentrations are calculated on the numeric weather prediction model grid. The complete meteorological information is available with much higher temporal resolution in Eulerian simulations. The time step of the model is in the double-digit seconds range. The numeric weather prediction model operated by the German Weather Service is based on the latter principle. Eulerian models offer better results when it comes to large-scale and longer-term simulations that cover multiples of the grid size used. However, a Lagrangian method is only as good as the underlying weather model from which the wind forecasts are derived. With already better temporal resolution of the models and finer vertical and horizontal resolution in the future, it will be possible to forecast dispersion calculations even for small-scale and short-term scenarios. ICON-ART, which was developed at the Karlsruhe Institute of Technology with the German Weather Service, can predict, among other things, reactive trace gases in the atmosphere. Current research is focussing on developing the model for smaller spatial scales and enhancing the flexibility of this

system so that a meaningful product is available in the shortest possible time (Figure 3).

PALM4U (PARallelised Large-eddy simulation Model for Urban applications) was also the subject of initial investigations for the short range (50 m to a few kilometres). Due to the integration of a chemistry module and the connection of PALM4U to the numerical weather prediction of the German Weather Service, this development must be pursued further. Technical resources are too limited at present to produce a time-critical product. It remains to be seen how the computing power of the next high-performance generations develops.

The Centre will continue to work with the German Weather Service on analyses of the availability, applicability and performance of existing dispersion models and those mentioned above.

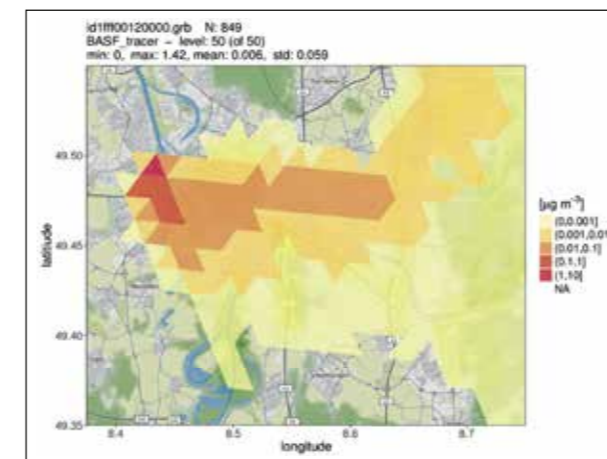


Fig. 3: ICON-ART dispersion calculation; mass concentration ($\mu\text{g}/\text{m}^3$) of an unknown substance (12 h forecast, 1 km horizontal resolution, 50 vertical levels, representation of the lowest level)

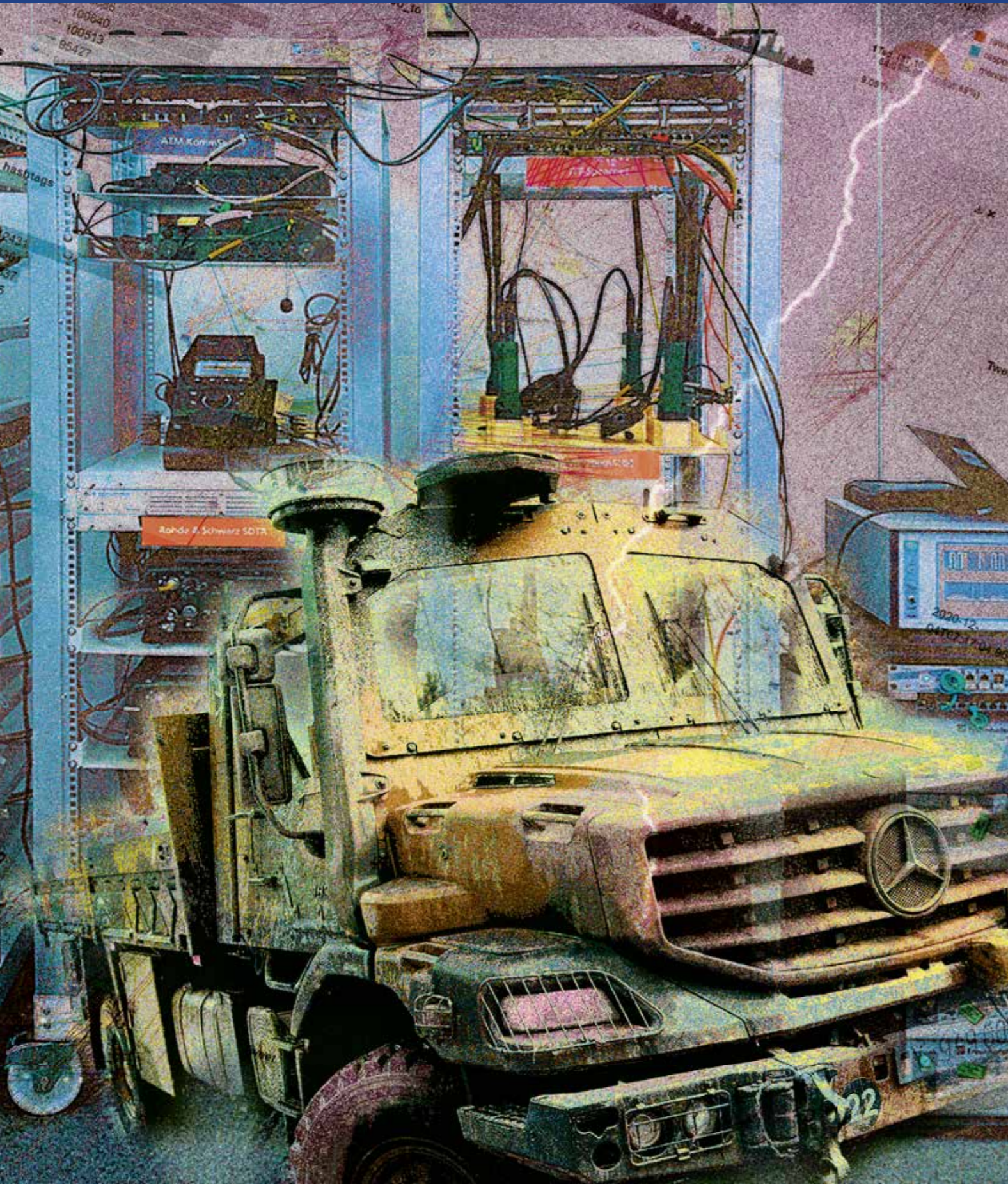
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Cyber and Information Technology Research

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 future conflicts, which will be increasingly hybrid.

What follows are several examples from the broad spectrum of research in this field. These include international activities, specific IT security tasks, different applications of artificial intelligence, and the challenges of hybrid conflicts.

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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Detecting hybrid threats in urban operations

Hybrid threats play an important role in current and future conflicts. They combine physical forces and (dis)information campaigns, regular and irregular forces, and take advantage of grey areas in legal issues and responsibilities. A solution being developed at the Fraunhofer Institute for Communication, Information Processing and Ergonomics can detect and assess hybrid threats in mission planning and execution.

Hybrid threats are not fundamentally new. They encompass physical power, information / disinformation campaigns, and regular and irregular forces and take advantage of grey areas in legal issues and responsibilities. As a result of the digital and global nature of current and future conflicts, they are having an increasingly important impact on mission planning.

It is difficult to clearly assign hybrid threats. They are designed to influence the decision making of adversaries, to entangle and demoralise, and to mobilise third parties for their own purposes – all this is done with clandestine activities in order to hide origin and intension. What seems at first to be a series of coincidences, actions by individual groups without any common target, or misunderstandings is in fact based on an elaborate system. The aim is nothing less than to shatter the “centre of gravity” and thus the foundations of the adversary.

In the “Detection of hybrid threats for urban operations” project, decision support for mission planning is being developed in order to detect and assess hybrid threats. The idea is a flexible and extendable suite of sensors and analysis modules which

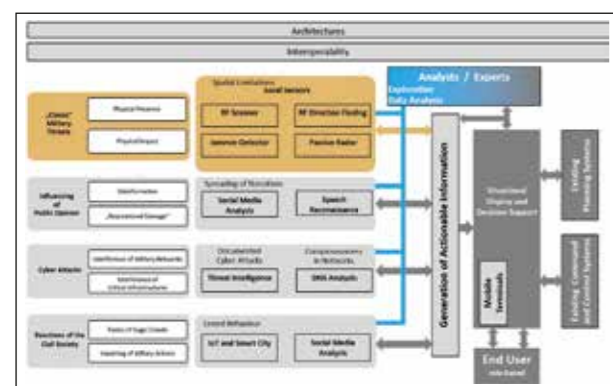


Fig. 1: Design of the demonstrator

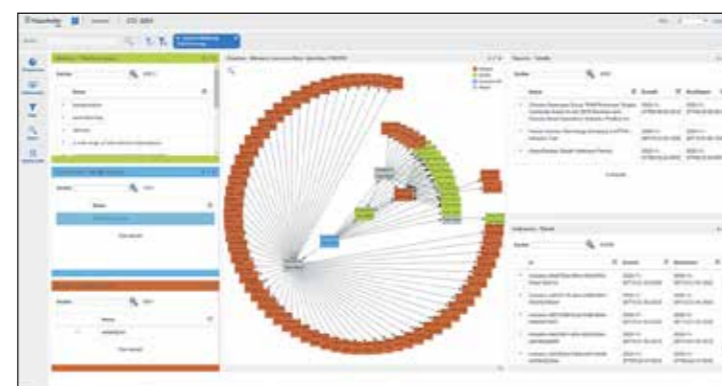


Fig. 2: Dashboard for explorative data analysis for the Cyber Threat Intelligence sensor

generates information about relevant domains. Knowledge of physical movement, effects in the electromagnetic spectrum, and actions in the cyber and information domain will be combined. In this way, users obtain a comprehensive assessment of threats for mission planning and execution.

Differences in time, location and relevance of information pose a challenge. The bearing of an unmanned aerial vehicle can be precisely determined in terms of time, location and accuracy within the sensor range and in real time. For actions in the cyber and information domain, the time and location of impact in the physical world are shifted. This project uses a wide variety of sensors available at the Fraunhofer institute and combines these in a demonstrator (Figure 1).

In order to support the mission-planning process, this project uses a fictitious troop-deployment operation similar to Defender Europe 20. Real data and lessons learned from this operation can be implemented in the evaluation. Additionally, current findings from the COVID-19 pandemic and related protests are used. By combining this in an overall use case, we can evaluate a solution for mission planning with many aspects.

The added value for military users will come from the comprehensive support for various participants in mission planning and execution. Edge processing of sensor data by the reconnaissance branch, situational awareness assessments of experts and analysts, and the amalgamation of data in a situational display all contribute to overall situational awareness. Figures 2 and 3 show different screenshots of explorative data analysis for threat assessments in the cyber and information domain. The role-



Fig. 3: Dashboard for explorative data analysis for the Social Media Analysis sensor

based integration of mobile terminals and interfaces into existing mission-planning and command-and-control systems is a general solution (Figure 1).

The general approach is to provide optimal support for different types of users but without offering a fully automated system. The amount of data and the complexity of detecting and assessing hybrid threats can only be addressed through appropriate man-machine cooperation. This cooperation is finely coordinated with various stakeholders (Figure 4).



Fig. 4: Stakeholders of the Bundeswehr and international agencies

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Interoperable cloud computing

The findings of the Interoperable Cloud Computing (IOCC) study series provide fundamental insights and technical principles with regard to implementing cloud computing in the Bundeswehr. These studies make a valuable contribution to establishing future-proof IT infrastructure. The findings will be directly used in HERKULES projects.

The IOCC study series was established in 2012 and ended in 2020. The studies originally focused on a theoretical analysis of cloud technologies for the Bundeswehr. However, they also provided concrete technical approaches and direct trials of cloud computing. Multivendor capabilities with VMware's Cloud Stack were studied in 2019. Various test scenarios confirmed in 2020 that this approach is viable and should be pursued. The cloud computing test bed is now ready for service and can be used to test software and use cases.

A main focus of IOCC in 2020 was container platform components based on VMware PKS with Kubernetes Cluster (Figure 1). This conglomerate will be a fundamental part of cloud-based infrastructure, to which existing IT services and applications of the Bundeswehr will migrate.

Figure 2 shows the underlying architecture, the hardware (computers, storage, networks), infrastructure as a service (VMware and Kubernetes), platforms as a service (e.g. SAP cloud platform), and software as a service.

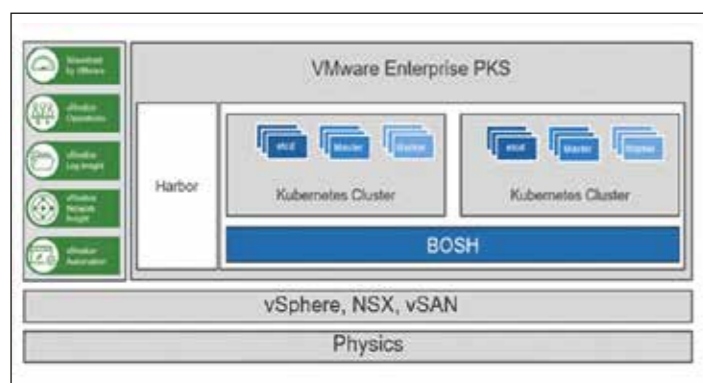


Fig. 1: Container platform (source: BWI GmbH)

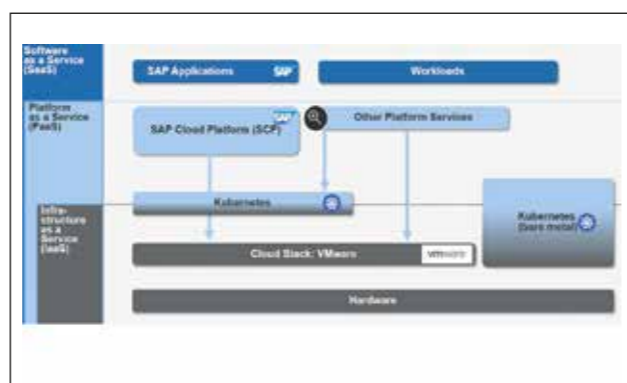


Fig. 2: pCloudBw architecture (source: BWI GmbH)

Figure 3 shows the functional target of cloud infrastructure. Important parts of this concept will be implemented from 2021 onwards as an upgrade to the scope of the HERKULES contract that was concluded between the Bundeswehr and its primary IT service provider, BWI. The focus is on technical IT services as well as migration services that serve to retrofit established applications to a cloud-based infrastructure.

Technical IT services include storage, virtualisation, operation system, and container technology at the infrastructure level. Platform services such as virtual desktop infrastructure, big data, and web application platform services are addressed in this target architecture. Geoinformation services and SAP applications are further frontend services for which the cloud will provide an infrastructural base.

The IOCC study series provided significant input for all of the above services and has facilitated progress towards an extensive and up-to-date cloud platform.

Cloud computing will have a substantial impact on the future IT infrastructure of the Bundeswehr. Electrical power supply and climate control will be determining factors for the design of modern data centres. In addition, aspects such as scalability, self-service, and service improvement processes (DevOps) will have organisational implications.

DevOps (development & operations) and the related agile approach will also have an effect on the provisioning processes of software products. Continuous integration and continuous delivery / deployment (CI / CD) were also addressed in the IOCC study series.

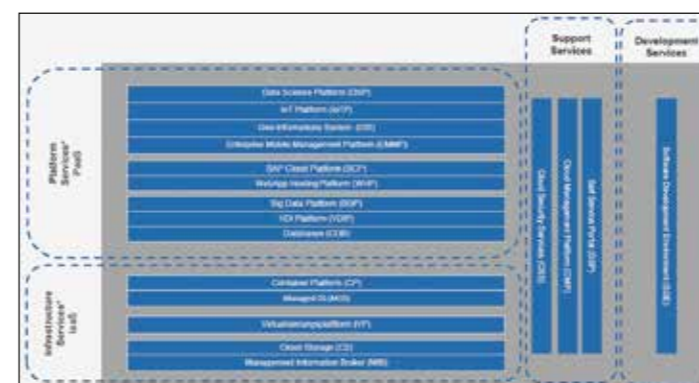


Fig. 3: pCloudBw target concept (source: BWI GmbH)

Technological developments (e.g. bare metal (aka metal as a service)) will affect future IT infrastructure as well as organisational considerations at work level. As part of these considerations, "migration as a service", a process developed in the IOCC study series, will be used in connection with the cloud computing reference architecture of Bundeswehr, which is also an IOCC development.

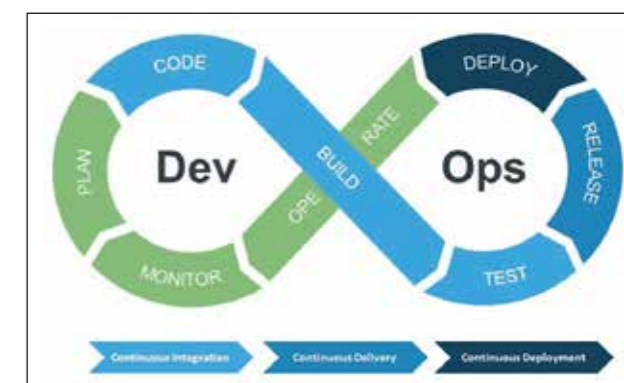


Fig. 4: DevOps (source: BWI GmbH)

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Weather data control

“Train as you fight, fight as you train” – Weather conditions must be considered in military operational planning, in reality as well as in training and exercises. Army simulation systems lack this capability. This project is designed to close this gap by using output data of weather models combined with rules of engagement.

Weather conditions affect the success or failure of military operations. This is proven in history, is still valid today, and of course will be true in future as well (Figure 1). Weather must be considered in decision-making and planning processes and in the execution of tasks (Figure 2).

In accordance with this principle, weather-related aspects must be integrated into different types of training. Computer-assisted exercises are a special kind of training performed at the Army Warfighting Simulation Centre (Figure 3). There are two staff training simulation systems (constructive simulation systems) and one virtual simulation system (virtual reality) at the Centre, in which weather conditions are rudimentarily implemented without taking account of realistic physical processes, their interrelations, and their progression over time. There is also no verification of temporal or physical plausibility over time. For example, snowfall can immediately follow clear summer conditions.

The aim of the first stage of the Weather Data Control project is to provide the constructive simulation system GUPPIS, which



Fig. 1: Thunderstorms – a local phenomenon with major consequences (source: Pixabay)



Fig. 2: Wheeled vehicle on difficult surface conditions

is used at the Centre, with realistic data on the impact of weather on materiel and military units in order to simulate effects and consequences and to train command staff in a more realistic manner. An additional aim is to verify the principle, pre-process the weather data and materiel characteristic parameters, and provide consequence data to the system in a predefined, standardised format. In future, other simulation systems will receive this data.

The project focusses on reasonable weather mapping, usability, acceptance among users (both operators – the secondary training audience – and the training squad – the primary training audience), a modern approach, the flexibility of software architecture, and ease of expansion. The project and the principle itself are based on different studies performed prior to the project start to verify whether the selected simulation system can deal with the proposed data and to evaluate possible effects to be realised within this project. The product will use data produced by the German Weather Service in its weather models. Data will be provided in a standard format that is used to transfer grid-based weather data and that is internationally approved by the World Meteorological Organisation. Data will be stored in a directory-based structure for later use. There will be no real-time weather representation in the simulation.

Stored weather data will serve as input for training. Models will calculate, weigh and evaluate specific consequences for certain materials or other entities in the simulation system based on technical and tactical restrictions and on the current training scenario and its goals and the given atmospheric parameters. To ensure quality and plausibility, there will be a module for reviewing and editing data prior to the final

output, with which meteorological products can be generated for briefings. Approval has been given to the basic concept and the evolved, refined version, in which software architecture, user interfaces, use cases, data formats, and interfaces are defined.

Upcoming tasks include the development of simulation-specific models, a browser-based user interface, and a backend. The project is scheduled for completion in late 2021.



Fig. 3: Army Warfighting Simulation Centre (source: Gefechtssimulationszentrum Heer)

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CWIX under COVID-19 conditions – The perspective of communications focus area

Due to the COVID-19 pandemic, NATO's premier interoperability event Coalition Warrior Interoperability Exercise had to be migrated from an event in Bydgoszcz, Poland, to a distributed event. This change in the final planning phase imposed special challenges for the Communications Focus Area with its low-level networking and tactical experiments. This was handled via the introduction of special VPN solutions and distributed online data analysis.

The Coalition Warrior Interoperability Exercise (CWIX) is NATO's premier interoperability event. The command & control (C2) capabilities present at CWIX span the complete communications and information systems (CIS) spectrum and represent the current, near-term, future and experimental capabilities of NATO and its partner nations.

Traditionally, CWIX focused on the strategic level with wired network infrastructure. An important focus of CWIX is Federated Mission Networking (FMN), whose development follows a spiral model. FMN spiral 4 was the first spiral to address the tactical edge and mobility. The resulting new requirements and interfaces must be addressed from the lower radio and network layers up to applications and procedures.

One of the main FMN-related focuses of the Communications Focus Area (Comms FA) in 2020 was on the verification of and last changes required for the Spiral 4 specification regarding Protected Core Networking enhancements and the Joint Dismounted Soldier System (JDSS) as a first step towards the tactical edge. In addition, the Comms FA laid the foundation for the



Fig. 1: Vehicle radio experiments



Fig. 2: Waveform interoperability tests

exploration of Spiral 5+ related technologies for the tactical edge. This way, the FA supports the work of the Tactical Edge and Communications Syndicates.

For normal CWIX execution, the Comms FA has special requirements for setting up experiments such as access to antennas for radio over-the-air interoperability tests and satellite reachability (see Figure 1a/b). For all over-the-air radio tests with military radios, applications must be made for frequencies. These steps had already been performed for CWIX 2020 when the decision for a fully distributed event due to COVID-19 was taken at the Final Coordination Conference. An alternative to co-located experiments had to be found in a short timeframe and had to support low-level network experiments. To achieve this, dedicated Layer-2 virtual private networks (VPN) were designed and set up (see Figure 2), allowing for virtual ethernet cables between labs. In addition, the means for radio network emulation and a special data acquisition and real time analysis framework were set up. For JDSS tests, Layer 3 CWIX infrastructure was sufficient.

In order to support the exploration process, for example for FMN Spiral 5+, detailed insights into the experiments are beneficial. This is also important for maintaining a high standard for documentation. Due to the distributed nature of multinational experiments, this is a major challenge. For this reason, this year also saw the introduction of a scalable measurement and analysis infrastructure in the Layer-2 VPN which supports data acquisition and the correlation of multiple layers, unified data distribution and logging, mechanisms to process/analyse/store information using big data mechanisms, and the live visualisation of data.

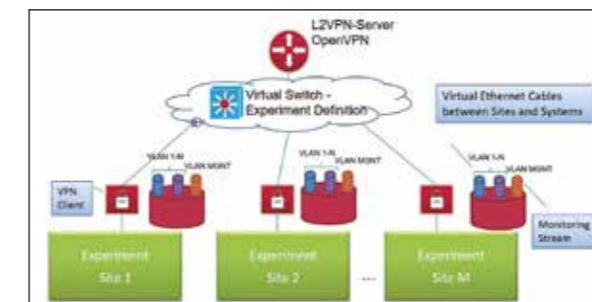


Fig. 3: Layer-2 VPN setup

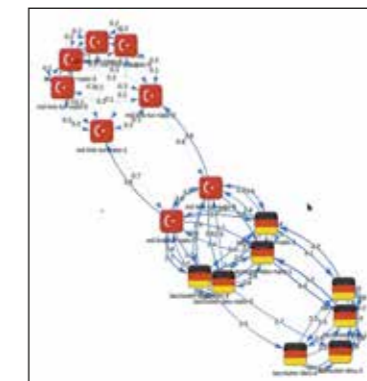


Fig. 4: Coalition network before national split

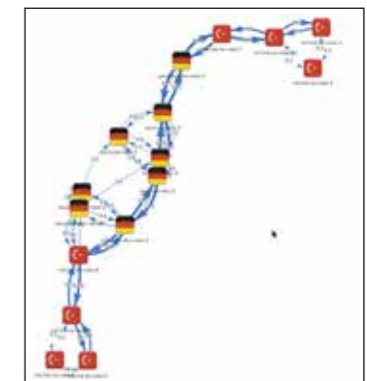


Fig. 5: Coalition network after national split

Figure 3 shows an example of a live visualisation and analysis of a routing experiment in the tactical edge with two national domains and one joint coalition domain (the six nodes in the centre). A split was performed in one national domain. This situation was handled by OLSRv2 (OLSR: Optimized Link State Routing), which acted as a coalition routing protocol. In response to the split, it tunnelled data through the other nations' routing domain. The resulting network topology can be seen in Figure 4. The bold arrows represent test traffic flow.

The introduction of Layer-2 VPN for networking experiments between distributed labs and an additional integration of live experiment analysis mechanisms ensured the successful ratification of FMN Spiral 4 and provided a solid basis for Spiral 5+ in the tactical edge. In addition, the measures were designed as long-term infrastructure for the preparation of experiments in different FMN communities also between CWIX executions and for a possible future hybrid CWIX.

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Automation and artificial intelligence in the ErzUntGlas research study

While the Digitalisation of Land-Based Operations programme is currently creating a basis for network-enabled operations, the ErzUntGlas (creation of a transparent battlefield to support dynamic operations) research study aims to analyse automation on the future battlefield.

By 2023, tactical teaming between soldiers and unmanned aerial systems will be demonstrated in cooperation with the Army in real scenarios under operational conditions. Such systems will be an ergonomic challenge for users, but from a technical point of view they mark a step towards the automation of processes using various types of artificial intelligence.

A first demonstration showed the interaction of the different systems. The physical tactical network includes military and civilian radio components and uses a software-defined radio with a stand-alone mobile radio system. Since the network topology is subject to permanent changes during operation, artificial intelligence processes will be used for optimum routing.

Microservices independent of this physical layer will be used to connect further command and control information systems via standardised interfaces in a service-oriented way. This was demonstrated for the future infantryman (TacNet, Figure 1) and an Israeli tactical command and control system (Fireweaver, Figure 2).



Fig. 1: Future infantryman with TacNet command and control system



Fig. 2: Interconnection of different command and control systems

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Apart from the involvement of human users in such a system (infantrymen, combat vehicle crews, command posts), the unmanned systems will be integrated to improve the physical connection by means of communication drones and to provide automated reconnaissance. In the future, specialised aerial photo interpreters will be replaced by a deep-learning mechanism integrated into each reconnaissance drone and designed to perform pre-classification.

This demonstration trial was performed in a test laboratory. One task was to detect people. They were identified by drone sensors and integrated into the system. In the future, a maximum of 16 unmanned systems will be used during operation, and the challenge will be to help the operator verify the results in an intelligent way and to continuously create an aggregated overall picture for a transparent battlefield.

The paths for reconnaissance drones will be defined by means of swarm intelligence, depending on what is happening on the ground. Provisions are made for differences between tactical high-level commands such as attack, all-around, and defence scenarios (Figure 3).

Apart from this reconnaissance capability, systems such as ErzUntGlas may additionally be used to accelerate the engage-

ment process if the roles such as sensor, shooter and release are defined in the system. While humans remain part of the process, reconnaissance chains will become more and more automated.

Combat units may in future be equipped with such information technology.



Fig. 3: Path planning for a drone swarm

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Multilateral interoperability programme

The aim of the Multilateral Interoperability Programme (MIP) is to develop a uniform standard for data exchange between heterogeneous command and control information systems in order to effectively support multinational and joint operations. Important improvements have been made with the new version of this standard, which has been released this year.

In international operations, for example in a NATO framework, communications between participating nations is important. It takes place via command and control information systems (C²I systems) with which the current operational situation, orders, and reports are exchanged. As different nations use different C²I systems, a uniform standard for data exchange is necessary.

This is the starting point of the Multilateral Interoperability Programme, which was founded more than 20 years ago. It has continuously enhanced its solution with regard to new operational requirements and technological progress. Currently more than 23 nations, the European Defence Agency, and NATO Allied Command Transformation are working together in MIP. The aim of MIP is to enable semantic interoperability between heterogeneous C²I systems in order to support multinational and joint operations effectively.

Important products of MIP are the MIP Information Model (MIM) and the MIP 4 Information Exchange Specification (MIP4-IES), which is based on the MIM. In Germany, the Fraun-

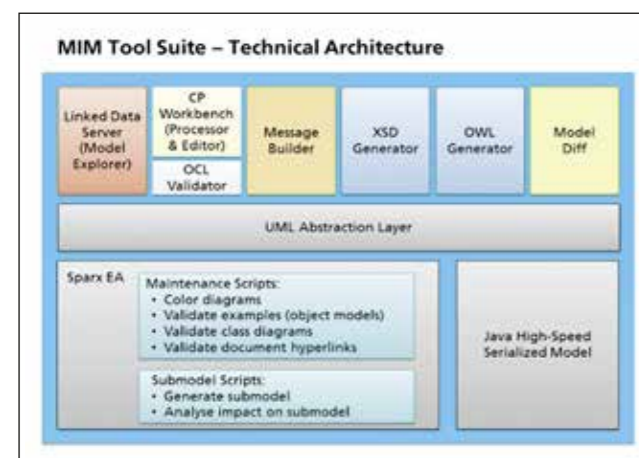


Fig. 1: MIM tool suite (source: Fraunhofer FKIE)

hofer Institute for Communication, Information Processing and Ergonomics has played a key role in the development of both products.

The MIM is an information model for the exchange of operational information. It has been continuously enhanced in recent years. In October 2020, MIP published version 5.1 of the MIM, which improves the description of sensors, dismantled soldiers, and tactical symbols. Furthermore, it covers additional requirements of the Air Force, which have been standardised with the Air Force Forces Command.

At the same time, numerous tools have been developed to support modelling work on the MIM and to ease usage of the MIM. One example is the Message Builder, which generates reporting formats as an XML scheme based on the MIM. These tools have been combined in the MIM tool suite (Figure 1).

The MIP 4 Information Exchange Specification (MIP4-IES) describes the exchange of information based on web services, for which the MIP Information Model is the semantic basis. Version 4.3 was published in October 2020. It uses MIM 5.1, which was published at the same time, as a basis. Due to the positive results of different tests during the year, MIP4.3IES has been included as the new exchange standard for Land C2 in spiral 4 of Federated Mission Networking (FMN) of NATO. It replaces MIP Baseline 3.1 from 2012 as the new FMN standard.

Work on MIP is done in MIP working groups, which meet four times a year at the Bundeswehr Technical Centre for Information Technology and Electronics in Greding as an international test site (Figure 2). The Centre provides administrative support to

these events and makes available its own IT infrastructure. This consists of two networks. MIP Conference LAN provides access to the document server and printer for meetings, and MIP Test LAN is used for technical experiments.

Due to the SARS-CoV-2 pandemic, the working groups were no longer able to meet and test on site in 2020. The Centre therefore installed an online collaboration platform so that working groups could meet virtually. The Centre also provided a VPN concentrator for remote testing.

With the publication of version 4.3 of the MIP4-IES, an important milestone for the project was reached. The future orientation of MIP is still under discussion. It is expected, however, that the MIM will be further expanded in the direction of a joint model.



Fig. 2: MIP working group meeting

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New techniques in the field of decompilation

To reduce the effort required to analyse unknown samples of (malicious) software, a research partnership between Singapore and Germany is exploring new techniques in the field of decompilation. Based on previous research at the Fraunhofer Institute for Communication, Information Processing and Ergonomics, a new decompiler is being developed and evaluated in multiple user surveys.

According to the Malware Statistics & Trends Report (AV-TEST GmbH), more than 100 million novel malware samples occurred in 2019. This represents a challenge to security authorities around the world. To address these increased hazards, a cyber defence research partnership between Germany and Singapore was established at the end of 2019. The main goal of this partnership is the recognition and analysis of malware. Since malware is typically only available as a binary representation without source code, the focus is on decompilation, i.e. the reconstruction of high-level structures from binary code to obtain source code-like output. In this way, the analysis of malware becomes simpler, which considerably reduces the effort required to analyse unknown binary samples.

A few years ago, a promising approach for restructuring control flow graphs called DREAM/DREAM++ was developed at the Fraunhofer institute. We are using this approach as a foundation for new research in the field of decompilation. The DREAM++ approach was therefore integrated into existing decompilers and was continuously improved. Initially, DREAM++ was integrated into the Hex-Rays decompiler.

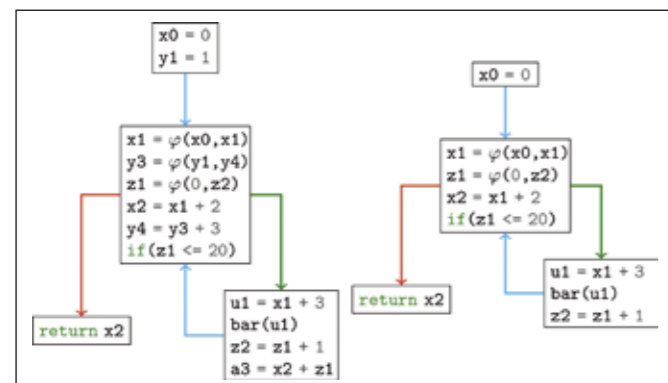


Fig. 1: Example of Dead Code Elimination. On the left, the control flow graph before, and on the right, after Dead Code Elimination

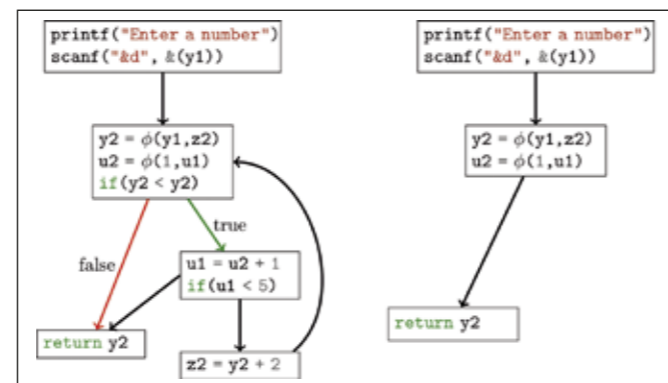


Fig. 2: Example of Dead Path Elimination. On the left, the control flow graph before, and on the right, after Dead Path Elimination

Further decompilers have since been developed and, after a thorough evaluation, we chose Binary Ninja as a platform for our further research. The main reasons for this are the stable and well-documented API (Application programming interface) as well as the opportunity to quickly implement new algorithms for the decompiler.

Based on Binary Ninja's intermediate language and the DREAM++ approach, we developed a new decompiler named dewolf. For this, we had to implement fundamental algorithms such as Expression Propagation and Dead Code Elimination. We also implemented various improvements and introduced new algorithms. In this way, we were able to enhance the quality of the decompiler's output in terms of correctness and readability.

One example of such a quality enhancement by improving an existing algorithm is Dead Code Elimination, which removes unused code. In the improved algorithm, we also managed to remove variables that depend only on each other and that are not used for everything else. Figure 1 shows the impact of Dead Code Elimination. Here, the variables y1, y2 and y4 depend on each other, which implies that traditional Dead Code Elimination does not remove the instructions defining these variables. Another example of an improved algorithm is the reconstruction of switch statements.

Furthermore, we developed new algorithms such as Identity Elimination and Dead Path Elimination, which is quite similar to Dead Code Elimination. However, instead of removing useless instructions, we remove code that the program never reaches. For example, in Figure 2, the branch condition $y2 < y2$ is always

false. Therefore, some part of the code is never reachable and can be safely removed, which simplifies the structure and makes analysis easier.

At the end of October, we conducted a user study to evaluate the current state of the dewolf decompiler. In this survey, we compared dewolf to the state-of-the-art Hex-Rays IDA Pro Decompiler and Ghidra, an open-source solution. Overall, the results show that the developed decompiler is already reaching a level that is similar to decompilers on the market. This also shows the potential of our research.

In the first part of the study, we showed each user code that was decompiled by one of the three decompilers. As can be seen in Figure 3, it turns out that, in terms of understanding, dewolf's output is as good as IDA Pro's output, whereas Ghidra's output is less understandable. However, dewolf's reconstruction of the control flow is the most natural.

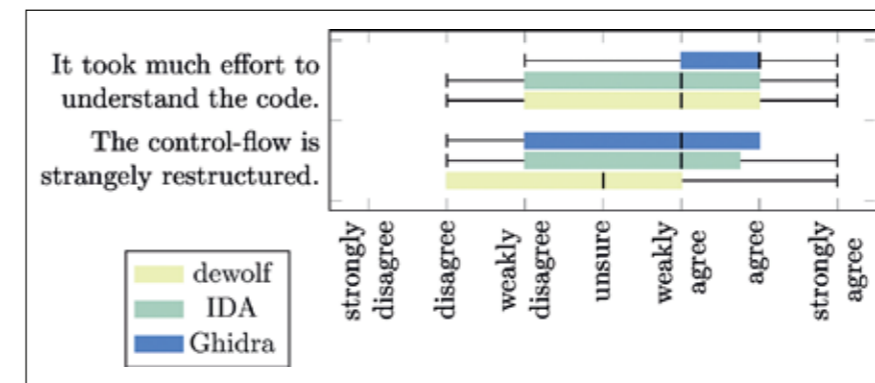


Fig. 3: Survey results for two questions of the decompiler survey, which was used to compare three decompilers

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A modular tactical router based on open standards

Studies conducted as part of the Modular Tactical Router research project (MOTOR) are laying the foundation for cross-technology tactical routing for national and international missions. The focus is on the further development of open standards in order to avoid vendor lock-in effects and, at the same time, to push deployment within NATO in the context of future Federated Mission Networking.

The MOTOR research project is investigating designs for a modular tactical router based on open standards. Such a system can be used to connect various IP-capable radios from the tactical domain. The tactical router spans a heterogeneous (ad hoc) network over which, for example, command and control information systems can communicate. In addition, support services such as language training are provided, as well as connections to other networks (Figure 1). Important performance factors are quality of service for IP-based voice, security and cross-layer mechanisms for coordination between the network and applications under changing communication conditions.

In 2016, two stages of a tactical router / mobile communication node laboratory demonstration and an associated demonstration at CWIX 2016 were successfully performed as a proof of concept. This included tactical routing based on OLSRv2 with DLEP support, quality of service with multi-topology capability, and the ability to connect legacy radios over stub networks. As early as this stage, layer 2 and 3 COTS/MOTS radios were supported. In addition, a special filter of routing protocol messages was

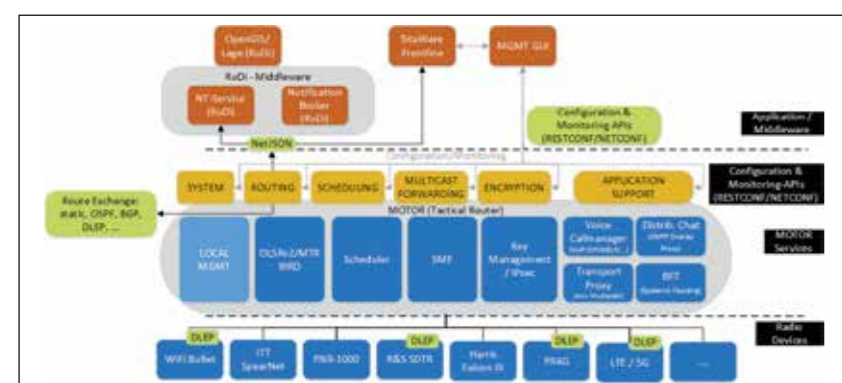


Fig. 1: Tactical router functionalities and interfaces



Fig. 2: Anglova scenario vignette 2, troop movement (source: NATO IST-124, published under Creative Commons licence for free use (see <https://anglova.net>))

implemented. This allows the mixed operation of slow radios (usually HF / VHF) with fast radios (usually UHF radios) without overloading the slow radios. Further contents were the integration of LTE and SATCOM as well as the integration of link-based security, SIP-based voice, and network visualisation.

In 2017, the applicability of MOTOR to the scenario of the EDA project TACTICS (Tactical Service-Oriented Architecture) was shown with OLSRv2 for network awareness for middleware including optimisations for slow and non-multicast-capable networks and a transport mechanism for TACTICS service discovery messages. The enhancements were presented at CWIX, including multicast support via SMF (simple multicast forwarding), MELPe transcoding for voice services, flexible use of voice spaces for group communication, and voice integration of SIP-enabled MOTS radios.

A scientific paper written together with the NATO group IST-124 demonstrated a significant improvement in scalability based on an enhanced multi-point relay (MPR) mechanism from MOTOR. This resulted in an overhead savings of approximately 90 % for 96 tactical routers in the Anglova scenario (Figure 2) in a relatively dense topology compared to OLSRv1 and OLSRv2 without MPR.

Motivated by lessons learned from the application in TACTICS, we improved the self-configuration capabilities of OLSRv2 in 2018 based on the automatic detection of link speeds and the use of policies. The DLEP concept was extended to 4G/LTE. In addition, initial approaches of interconnecting multiple tactical routing domains were investigated and successfully demonstrated at CWIX 2018.



Fig. 3: Experimentation environment of the tactical router

In 2019 and 2020, we investigated enhancements in areas of (unicast and multicast) routing, radio integration, network awareness and voice services, integration approaches of a transparent TCP proxy with multipath capability, and support for network coding. In addition, the management interface was extended, and an integration into an analysis and test environment (Figures 3 and 4) was driven forward to support the evaluation of the router in realistic operational scenarios. This was used as a basis for demonstrations at CWIX 2019 and 2020.

In the coming years, the concept of the tactical router will be further evaluated and standardised so that approaches can be incorporated into the definition of the next NATO architecture for the tactical domain in the framework of Federated Mission Networking.

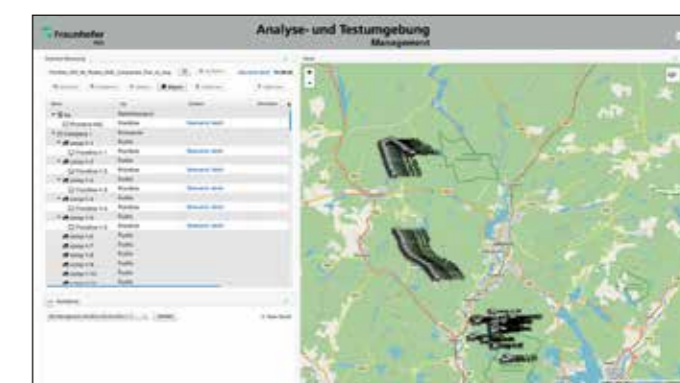


Fig. 4: Anglova scenario with 96 nodes in the analysis and test environment

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IP waveforms

Software-defined radio (SDR) has been a keyword for years when it comes to the performance of new radios. Thanks to SDR technology, waveform applications (WFA) can be loaded depending on situation- and mission-specific requirements. These radios have the advantage that not only old waveform applications but also new IP-capable WFAs are available for use.

An IP-capable V/UHF waveform (National Tactical Network WFA) is currently being procured as part of the Joint Networkable Radio Equipment (SVFuA) project and will be fielded before the end of 2020.

The Fraunhofer Institute for Communication, Information Processing and Ergonomics and the Fraunhofer Institute for Integrated Circuits are jointly investigating a flexible IP-capable waveform that supports rapid prototyping. This ensures better presentation and the introduction of national interests and waveform requirements in international projects. Such rapidly adjustable WFAs also have advantages for modern tactical uses.

FLIP, a flexible WFA, is characterised by a modular, scalable and reconfigurable design with cross-layer interfaces. Since 2016, the two Fraunhofer institutes have been providing IP-capable waveforms to CWIX. FLIP now offers various tactically and operationally relevant capabilities such as the simultaneous transmission of CNR-PTT voice and data, mobile ad-hoc networking (MANET), and the use of quality-of-service and cross-layer interface aspects. These have been successfully tested.

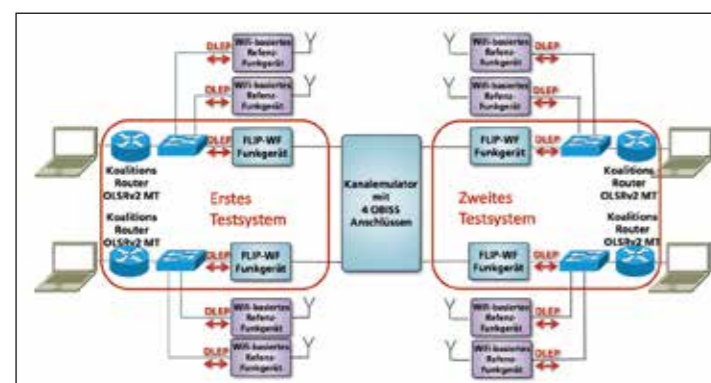


Fig. 1: Structure of the test setup consisting of the two test systems with two extended test sets each and connected by means of a channel emulator

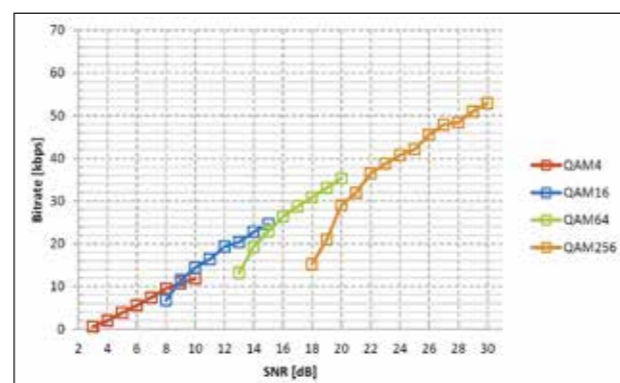


Fig. 2: Correctly transmitted data without header information in the MODERATE channel

Thus far, FLIP results and capabilities are as follows:

- Further development of national (Bundeswehr) capabilities with respect to waveforms and SDR
- Contributions to national and international operational waveforms
- First-time testing of new functionalities not covered by radios fielded so far in the Bundeswehr
- Identification of new technologies at an early stage as well as their quick and cost-effective test in practice

During the FLIP-WFA Phase 2 study, a waveform development and porting platform was adapted specifically to FLIP requirements by using a pseudo crypto module. The architecture and characteristics of this platform are similar to those of the Joint Networkable Radio Equipment project. As a result, it is highly suitable for porting further waveforms to this project.

The FLIP WF was also supplemented based on the specifications of STANAG 5630-33 Edition 1, and interoperability with other nations (POL, BEL, NOR) was demonstrated during CWIX 2019 for the first time.

The Fraunhofer Institute for Integrated Circuits analysed the portability and performance of modern broadband HF waveforms in the HDR HF project. In the laboratory, the transmitter/receiver modules of the Joint Networkable Radio Equipment project were linked with the test sets. Since the development of the Open Baseband Interface Specification for SDR (OBIS) interface used for the Joint Networkable Radio Equipment project was closely monitored by the Institute, its deployment via known protocols was possible in good time and without any problems. Only minor adaptations with respect to the protocol

behaviour of the test equipment software were required for the communication test. The performance of these WFAs was measured during laboratory and field tests. A Fraunhofer proprietary IP gateway was used to connect the higher IP layers. A special feature is the automatic repeat request (ARQ) algorithm used in the data link processor. This ensures reliable data transmission based on error detection and a back channel used to confirm that data are correct and to request re-transmission of incorrect data. In this way, the system can dynamically adapt the code rate depending on channel features. The higher the signal to noise ratio (SNR), the higher the code rate as well as the data rate.

During two field tests, HDR HF was tested using a radio link between the Bundeswehr Technical Centre for Information Technology and Electronics and the Bundeswehr Technical Centre for Ships and Naval Weapons, Maritime Technology and Research. Numerous tests with varying modulations and codings were performed. The tests included all modulations ranging from 4-QAM to 256-QAM. The SNR varied significantly during the test, but these variations were compensated for by hybrid ARQ technology. The waveform dynamically adapted to the features of the transmission channel and varied the code rate on the fly.

This demonstrated that shortwave broadband communication is possible and that it is suitable for IP-based networks.

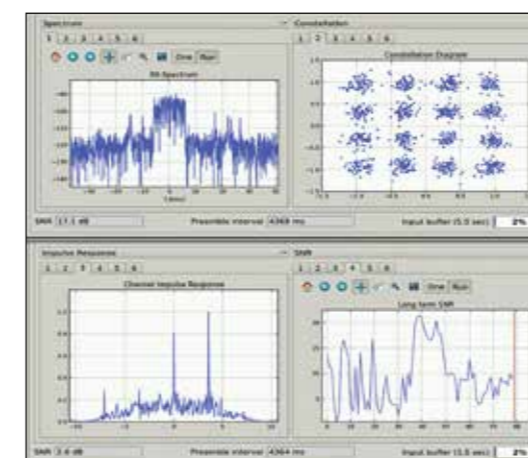


Fig. 3: Different representations of the HDR HF waveform



6

Appendix





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