TECHWATCH

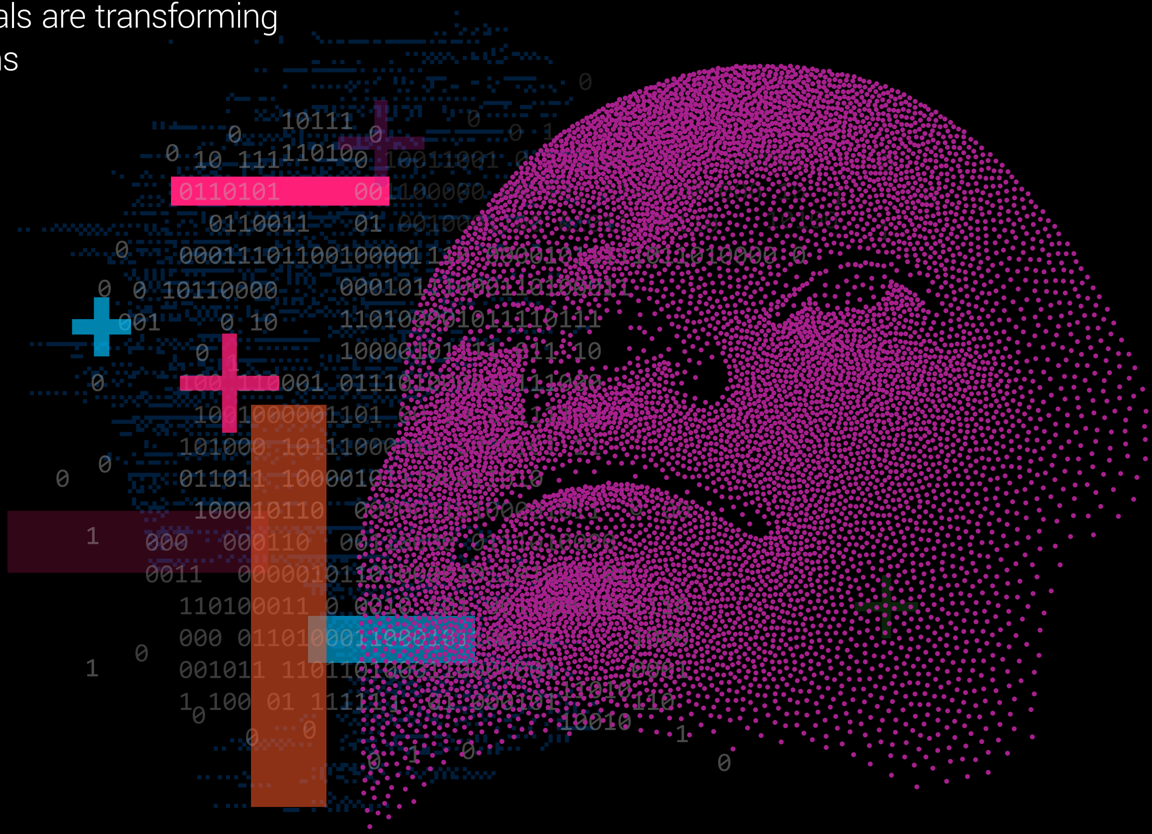
JULY 2023

Embracing the AI revolution

A material change for Defence and Security

The rise of AI
Will artificial intelligence command the military of the future?

The extraordinary properties of advanced materials
How novel materials are transforming Defence operations



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Foreword

Welcome to our thirteenth edition of TechWatch, where we explore emerging technologies that are set to change the face of the Defence and Security sector. We assess their impacts, opportunities and challenges, what we need to be mindful of and how to prepare for the future.

Given the surge in interest in all things Artificial Intelligence (AI), we have chosen to include this widely talked about subject area as one of our deep dives for this edition. We look at the rise of AI and explore how combining AI systems to create bigger, more complex systems can unlock true capability and the impact AI will have on Defence and Security from applications in surveillance, reconnaissance and cyber Security, to robotics and autonomy and platform management. We also discuss the need to develop counter measures to thwart adversaries, recognise misinformation such as 'deep fakes', how to tackle the subject of AI Assurance and what steps need to be taken to achieve and sustain tighter regulation of the global AI industry which, in 2022, was valued at $428bn[1].

Our second feature will take you deep into the world of advanced materials where we look at how science is driving the creation of materials whose exotic properties and almost supernatural characteristics are playing an essential role in our increasingly complex military systems. We discuss the curious properties of graphene with James Baker, CEO of Graphene@Manchester and how a graphene 'club-sandwich' has opened up huge potential to create designer materials and novel devices never possible before. We also look at metamaterials and their extraordinary capabilities, how state-of-the-art 3-D printing technology is impacting front-line operations.

In addition to our deep dives, our expert horizon-scanners have put together a collection of short news stories which discuss some of the ground breaking technologies and inspirational innovations that are currently in development across the globe.

We hope you find this an informative and enjoyable read and if you have any feedback or would like to speak to a member of the QinetiQ team, please contact us at TechWatch@qinetiq.com.

MIKE SEWART
Group Chief Technology Officer at QinetiQ

1. www.fortunebusinessinsights.com

CONTRIBUTORS

QinetiQ contributors
Dr Helen Dudfield
Richard Lane
James Ramsden (Naimuri)
Amanda Coleman
Mark Round
Claire Taylor
Robert Turnbull-Hall
Mike Sewart

External contributors
Gareth Appleby-Thomas, Cranfield University
James Baker, Graphene@Manchester
Assen Batchvarov, Quaisr
Idranil Pan, Quaisr

Editors
Amber Bradbury
Bryony Chinnery
Leah Daly
Luke Morton
Dr Mark O'Dell
Dr Daniel Reid
David Rosewell
Justine Vincent

Design & Production
David Stephenson
Jaime Newberry

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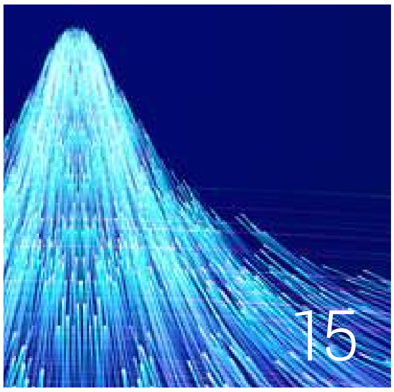

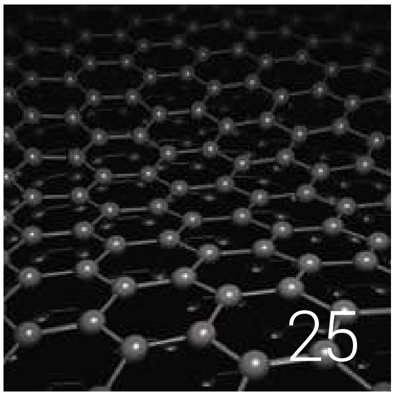

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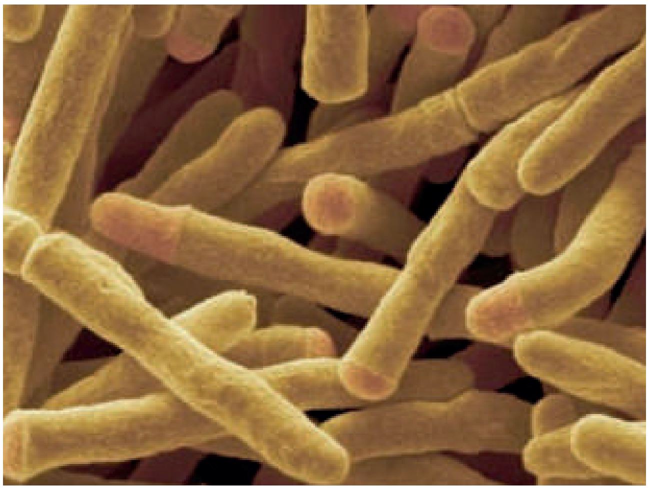
News



An enzyme that can turn air into electricity

Sometimes potentially harmful things can do something remarkable. In this case it is an enzyme from a cousin of the bacteria responsible for tuberculosis and leprosy. Whilst in the process of studying this bacterium, known eloquently as Mycobacterium smegmatis, Australian scientists have discovered the enzyme can convert hydrogen from our atmosphere into electricity.

The scientists, led by a researcher from Monash University, claim the enzyme, known as Huc, could provide a source of energy capable of powering a range of small portable electrical devices such as biometric sensors, environmental monitors, etc.

Huc is apparently highly resilient and "extraordinarily efficient". It can even consume hydrogen in places as diverse as Antarctic soils, volcanic craters and the deep ocean. When provided with more concentrated hydrogen, its production of electric current scales accordingly. The scientists believe it could be used eventually "in fuel cells to power more complex devices, like smart watches, or smartphones, more portable complex computers, and possibly even a car."

The research has been published in the journal, Nature.

Source: msn.com | Nature
Estimated time to maturity: 5 to 10 years.

Innovative interface enables touch technology through pumping liquid into an OLED display

Researchers from Carnegie Mellon University's Future Interfaces Group have designed an innovative Organic Light Emitting Diode (OLED) display that can create tactile sensations. Using what is known as "haptic technology", it depends on computer-induced forces, vibrations, or motions to provide the user with an artificial sense of touch.

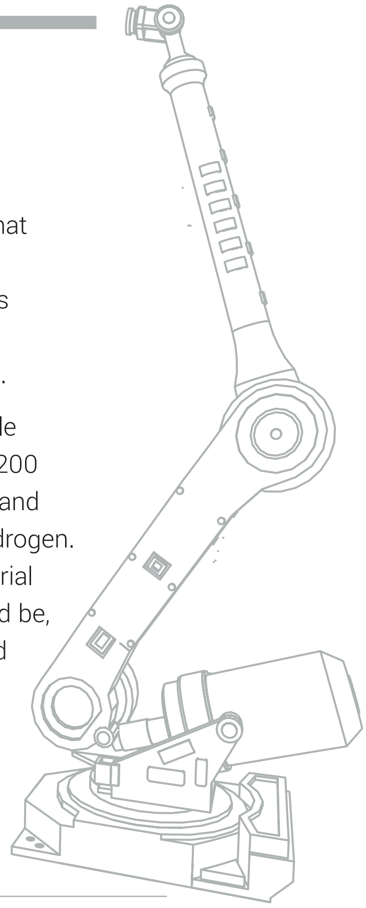
The research team call their invention 'Flat Panel Haptics' (FPH). It works by placing a layer, only 1.5 mm thick, embedded with tiny electro-osmotic pumps (EEOPs), behind a flexible OLED display. These pumps can then move liquids quickly within the haptic layer using electrical fields to cause shaped icons, such as buttons or keys, to pop out from the display.

Currently, the shapes are pre-defined and cannot be altered by the user, but the research team believe this could change in the future if the FPH technology is used to create small dot-matrix items. These could enable smaller and more diverse shapes.

Besides being useful for those who lack or are deprived of normal vision, one can envisage the technology being used for improving onscreen typing, gaming and in-car controls. For the military, such technology could be useful in low-light conditions such as covert operations.

Source: Carnegie Mellon
Estimated time to maturity: 2 to 5 years.

Image Credit: Future Interfaces Group at Carnegie Mellon



Hunting novel materials using AI robots

Scientists at the Lawrence Berkeley National Laboratory (LBNL) have succeeded in combining artificial intelligence (AI) and robotics to discover recipes for making novel inorganic materials that could improve the performance of batteries, fuel cells, and superconductors. This development, established within LBNL's Material Project, speeds up the process of synthesizing such materials which hitherto involved human effort. In fact, their new set-up, known as A-Lab, is already synthesizing about 100 times more novel materials per day than humans in the lab can manage.

LBNL's A-Lab is fully automated and can run continuously. Its AI starts by establishing a plausible approach to synthesizing a material and then guides robotic arms to select from among nearly 200 different powdery starting materials. After mixing these precursors, another robot parcels them and loads them into furnaces where they can be mixed with gases such as nitrogen, oxygen and hydrogen. The AI then determines other treatment, such as heating and drying times, before the new material is sent on to analysis to assess whether its structure and properties are as predicted and, if need be, iterate the approach taken to refine the result. The process drastically increases the creation and discovery of new compounds where the number of potential recipes is essentially infinite!

Source: Science
Estimated time to maturity: 0 to 2 years.

This Heat Battery Is Made Out Of Bricks and Could Be Key to Industrial Decarbonisation

Industrial heat production relies mainly on non-renewable fossil fuels, biomass or electricity to provide the consistent supply of heat needed for applications ranging from cement production to drying food. Moreover, with industrial heat amounting to almost one-fifth of global energy consumption, transitioning to renewable sources of heat energy is very important. To do this, we need to overcome the intermittent supply of renewably generated electricity to deliver continuous heat.

This is where the Rondo Heat Battery (RHB) comes in. It is the first electric thermal energy storage system in commercial operation in the US and takes low-cost, renewably generated electricity to provide stored and accessible heat. The RHB stores excess heat generated from the clean electricity for later use at a time when electricity and heat generation is low, such as during the night for systems utilising solar panels.

Unlike some electrical batteries, however, RHB has a simple design and is made from commercially available materials – bricks! This means that systems can be built quickly and will last 50+ years.

The RHB uses electrical heating elements, like those found in an oven, to generate heat from the renewably generated electricity. The electrical elements emit infrared radiation which warm up thousands of tons of brick stacked inside the RHB. These bricks reach temperatures of up to 1,500°C and can store the heat for hours or days with only very small losses of around one percent. When there is demand for heat, super-heated air or steam flows through the cavity containing the bricks, delivering megawatts of heat.

Unlike other heat batteries, the RHB is a low cost, 100% renewable system that does not require any flammable materials and is capable of delivering high temperature heat with 98% efficiency and it is a distinct step towards the decarbonisation of the global industrial sector.

Source: Rondo Energy | IEA
Estimated time to maturity: 0 to 2 years.

Image Credit: How It Works – Rondo Energy

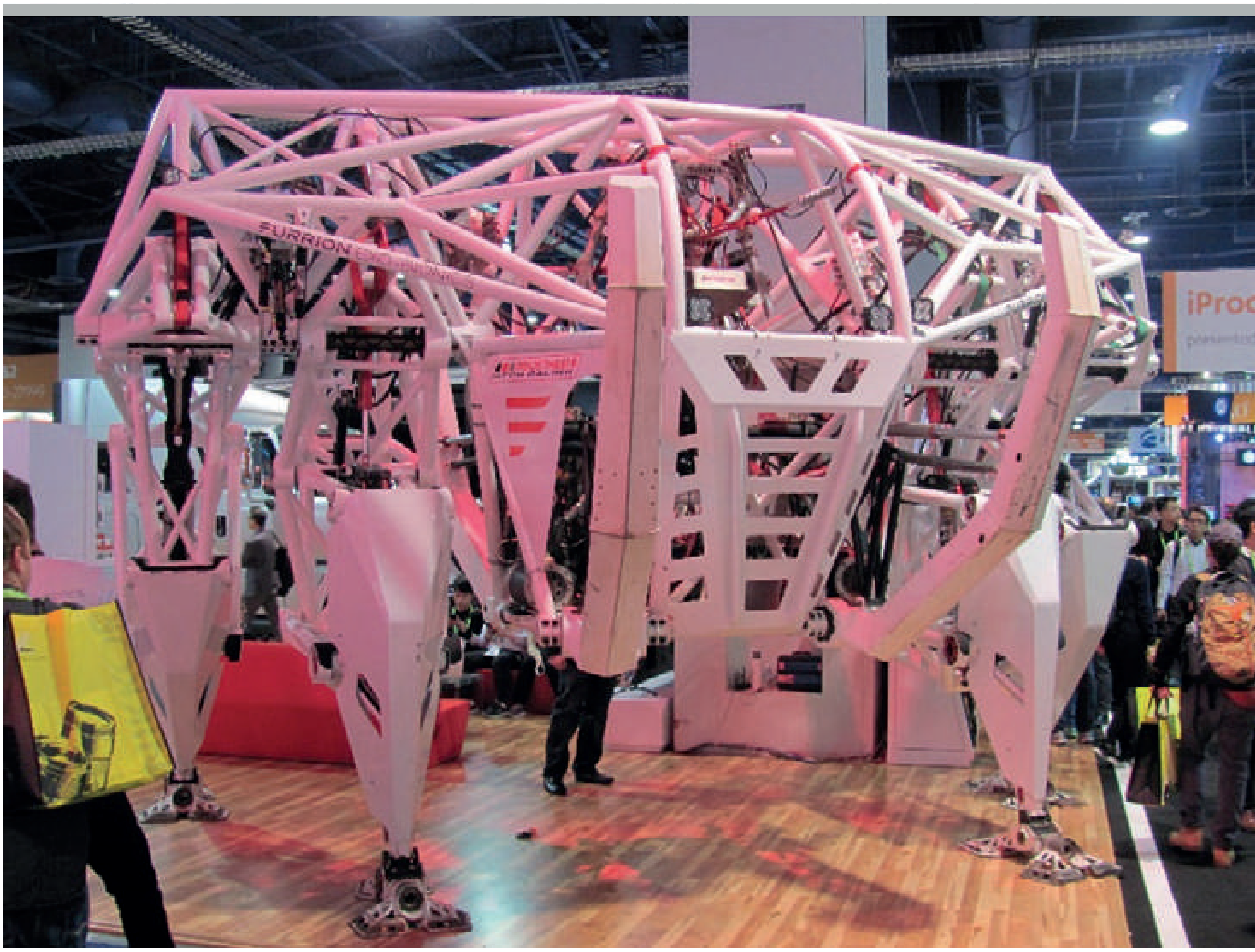


Image Credit: CES 2018

Mech Suit amplifies human strength fifty times

A Canadian engineer has developed a fully operational 'mech suit' that can amplify human strength fifty times. This is an extreme example of human augmentation, a field of technologies which can raise human performance above the normal level. The suit stands 14 feet tall, weighs nearly 9,000 pounds with 200 horsepower, and is 100 percent electric and human controlled.

The engineer, Jonathan Tippett, calls his invention 'Prosthesis' and claims it is the world's first fully operational mech suit. The suit was finished in 2017, but since then work has continued to get the speed, fidelity and responsiveness required whilst ensuring the tunability of stability versus a light touch. The suit was on display at the International Consumer Electronics Show in 2018, see image.

According to Tippett, the human, or rather pilot in the suit, wears a full-body exoskeletal interface. The pilot's arms control the outside legs, and their legs control the inside legs; there are four identical legs in a row. The exoskeletal interface has sensors on it that pick up the force the pilot is putting into it and amplifies that into the hydraulic system.

Exoskeletons and mech suits are of interest to the military. Smaller scale exoskeletons could improve the strength, endurance, safety, and ergonomics of soldiers as they walk, run, jump, climb, and manoeuvre on the battlefield. Prosthesis shows what can be achieved when these ideas are taken to extreme scales.

Source: Mech Suit
Estimated time to maturity: 0 to 2 years.

Visualising Images from Brain Scans Using AI

We have all seen the recent advances in AI systems being used to produce stories, write code, or draw pictures. Now, a team from Osaka University in Japan have combined their own Machine Learning model with an AI image generation system to produce images of what people are seeing, using their brain scans.

The team fed their model with functional Magnetic Resonance Imaging (fMRI) scan data from four different participants who each viewed a dataset of 10,000 images. Building upon established work, their model is able to interpret this fMRI data to produce text-based descriptions of the images that the subjects had viewed. The researchers then inputted these descriptions into the AI image generation system called 'Stable Diffusion', which produced images based on these text prompts.

The text descriptions produced by the model, and the images that Stable Diffusion was able to generate from them, demonstrates that a significant amount of information about the images being viewed exists in fMRI scans and can be extracted from these scans using this system. At the moment these images are quite abstract when compared with the original, however this demonstrates a successful and impressive proof of concept. As the amount of information detail able to be extracted improves, it is likely that the resulting text and images will become increasingly more accurate recreations of those originally viewed.

The researchers have linked this work to other ongoing research programmes looking to extract information from memories, while a subject is visualising previous events and images. If further developments allow sufficient information to be extracted in this way, this could have massive implications, both positive and alarming: potentially making science fiction a real capability for solving crimes by viewing a suspect through a victim's eyes, or stealing sensitive information by scanning a person.

Source: biorxiv.org
Estimated time to maturity: 5 to 10 years.

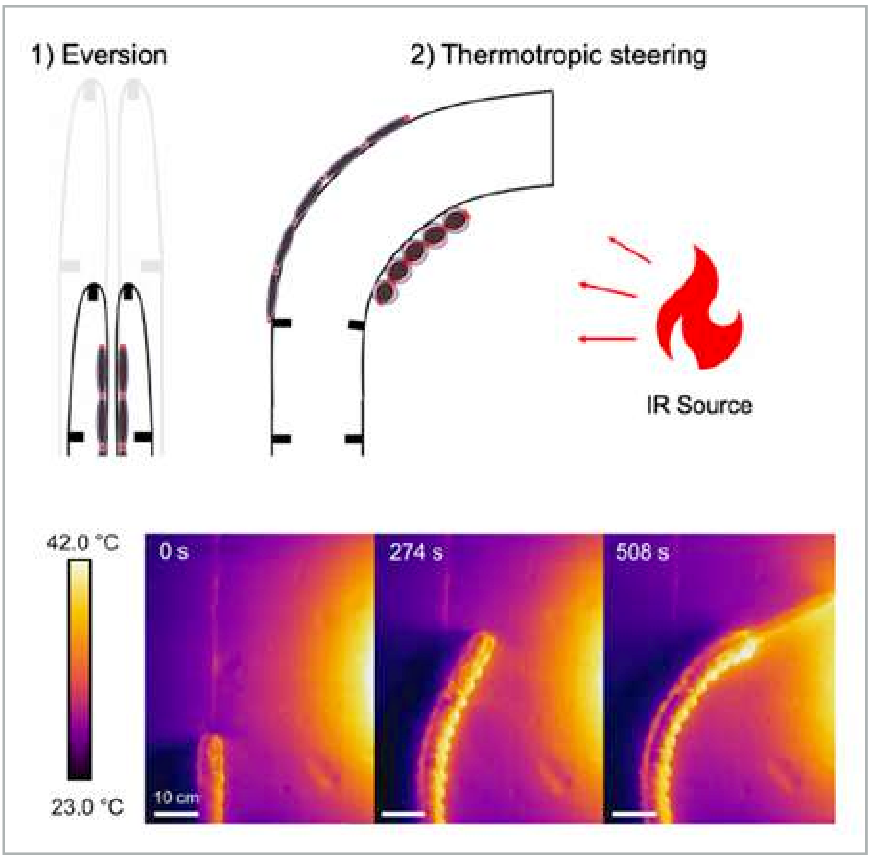


Image Credit: arxiv.org

Heat Seeking Robot Could Detect and Fight Fires

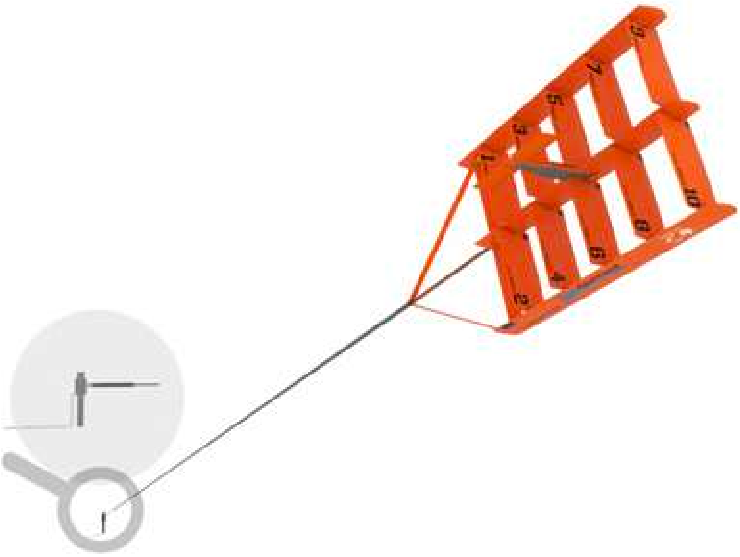
Nature continues to inspire many of our inventions and developments and one of the most recent of these is a robotic tendril that can react to heat sources and steer towards them. This behaviour mimics the way vines and roots will search for light and water respectively and grow towards them.

Researchers from the University of California have produced a vine-like robot consisting of a series of pneumatic artificial muscles, dubbed sPAMs, connected on either side of a flexible tube. These sPAMs each contain a fluid which evaporates rapidly when exposed to heat via infrared radiation. This causes the sealed sPAM vessel to change shape from a long cylinder to a sphere, which in turn causes the series of "muscles" to contract, shortening the length of the side that has been exposed to heat. Through this mechanism, the robot steers automatically towards a heat source, with no outside control or input required.

Decentralised and autonomous systems such as these have many benefits, such as reducing the amount of monitoring and processing required, as well as broadening the capacity of the system to include tasks too dangerous for humans, or in areas where access is restricted. The researchers have also detailed how the materials used can be tailored to individual conditions and situations, allowing the response of the device to be tailored to specific needs. Systems like this could be utilised within engine and plant rooms, or in chemical, biological, radiological or nuclear (CBRN) contaminated areas, for example.

This technology could also be developed to work in three dimensions, allowing for greater navigation and access. A further goal of this system could be to develop the "vines" to carry fire suppressing systems or chemicals, allowing them to attempt to put out fires when detected.

Source: arxiv.org
Estimated time to maturity: 5 to 10 years.



Underwater Kites Promise Versatile Hydroelectric Power Generation

In order to keep up with increasing localised and global energy needs, to ensure energy Security, and to combat the ongoing climate crisis, new and innovative methods of energy generation are needed. One such example of these is being developed by SeaQurrent, a Dutch start-up aiming to make harnessing tidal current, ocean, and river power more accessible.

SeaQurrent's research team have designed an underwater "kite" that can be used to create electricity by exploiting a wide range of different ocean conditions, such as shallow or deep water areas with fast or slow moving currents. The kite sits suspended in the water, tethered to a power generation hub and as the water moves, the kite generates a substantial amount of force, which is converted into electrical energy using a hydraulic cylinder and a hydro motor-generator combination.

This technology aims to be quicker to deploy, requires less infrastructure than previous systems and it is safer for the environment, having less impact on surrounding marine life because its movement is slower than that of other systems. These improvements increase the versatility of the system, and allow it to be used in a wider range of areas.

Source: SeaQurrant
Estimated time to maturity: 2 to 5 years.

Acoustic sensing glasses enable silent communication

A Cornell University researcher, Ruidong Zhang, has developed so-called "sonar glasses" that can enable silent communication. These eyeglasses are able to read the words that the user mouths to enact silent commands to pause or skip a music track for example, or enter a passcode without the need for a keyboard. This silent means of communication uses eyeglasses, which are fitted with miniature microphones and speakers, as a silent-speech recognition interface called EchoSpeech. EchoSpeech uses acoustic sensing (or sonar) to send and receive soundwaves across the face to sense lip and mouth movements and a deep learning algorithm analyses the resulting echo profiles in real time. The current system can recognise up to 31 unvocalised commands and is able to analyse the echo profiles with an accuracy of approximately 95 percent. Cornell proposes that EchoSpeech could be used to communicate silently with other people via a smartphone in places where speech is inconvenient or inappropriate, or to enable people who are unable to speak to communicate more easily. This technology could be useful in government or military applications where privacy and sensitivity is important and given that the data is processed locally on your smartphone instead of being uploaded to the cloud, privacy-sensitive information never leaves your control. As EchoSpeech audio data is much smaller than image or video data, it requires less bandwidth to process and less power, resulting in longer battery life.

Source: Cornell University
Estimated time to maturity: 2 to 5 years.

AI

DEEP DIVE

Will Artificial intelligence command the military of the future?

Right now, it's impossible to browse the news, social media or a magazine without seeing a mention of Artificial Intelligence (AI). It seems to have infiltrated every part of our lives, from simple writing jobs to self-driving cars and complex surveillance systems.

But where has AI come from and why has it suddenly become so prevalent? We provide a general introduction to the technology, its applications and its relevance to Defence.

What is Artificial Intelligence?

AI is a field of computing that focuses on systems which can perform tasks that typically, or previously, required human intelligence to complete: learning, problem-solving, decision-making, perception, creativity and social engagement.

Often the terms AI and Machine Learning are used interchangeably. While they are closely aligned, the core difference is that AI is based on the general idea of a machine that can mimic human intelligence, whereas Machine Learning leverages data and observed patterns, specifically with the aim to teach a machine how to perform tasks and provide results.

Arguably, the earliest body of work in AI was undertaken by British mathematician and computer scientist, Alan Turing, in the mid-20th century. The ‘Turing Machine’ concept described an abstract computing machine moving through its limitless memory, learning and predicting from previous patterns. While this may be considerably different to the software hitting the market in the present day, the concept of a machine that is able to learn, modify or improve without being explicitly programmed to do so, is the essence of all AI.

The rise of AI

While the idea of AI may have existed for nearly a century, the more widely recognised applications of AI and machine learning techniques were developed around a couple of decades ago.

At the time, computing power and storage was an extremely expensive commodity and meant that high-powered computing could mainly only be explored by professionals in the computing field and those with access to specialist machines. As the prevalence of devices and internet connection skyrocketed in the late 90s and early 2000s, and the cost of processing and data storage dropped, the ability to handle big data sets within the average professional or even personal computer environment became more of a reality.

This coupled with developments in sensor technology, which enabled better data collection and situation awareness, an increase in data available online, and the rise of cloud and edge computing methods, saw a simultaneous increase in the need to process more data, faster, and a desire to have machines take on the burden of many human activities.

AI hitting the headlines

As with all trends, technology and beyond, it takes a few high profile use cases to turn the process into a recognised household concept.

One of the first companies to break through in this space was Google’s sister company, DeepMind. Over the past decade, they have developed algorithms that are able to beat professional gamers, created a protein-folding prediction system, capable of predicting complex 3D shapes of proteins and even established programmes for medical applications such as disease diagnoses in eyes.

However, the application that has made the biggest impact worldwide to date is ChatGPT, a sophisticated chatbot-style AI by OpenAI that enables you to ask complex questions and receive answers based on its globally available data. The platform clocked over 100 million active users in just two months and left many users unable to use the system as its servers struggled to cope with global demand. ChatGPT, and others like it, are based on a type of AI called Generative AI (Gen-AI). This form of AI has the sole purpose of generating new content based on patterns in existing data or information. Where ChatGPT uses text and language, other Gen-AI programmes exist to create different media such as art, music and photography.

While ChatGPT was certainly the first of these tools to hit mass consumption, others to watch in the coming months and years include Google’s Bard, Microsoft Bing (based on OpenAI technology), ChatSonic and Ernie by China’s Baidu social media app.

Can you tell the difference between AI-produced or human-created content?

One of these articles about the future workforce and AI's impact was written by a human, one by ChatGPT but which is which?

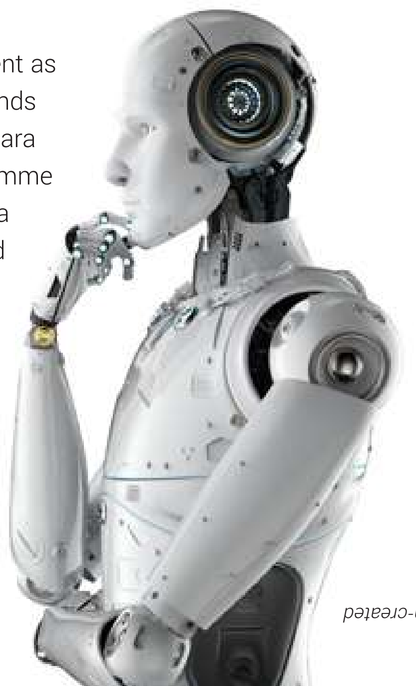
Example 1:

Will AI take over human jobs?
There is a lot of chat about robots and AI stealing the jobs of humans and eventually making us obsolete. While AI is certainly changing the way we work and increasingly will be able to complete jobs quicker and better than humans will, currently there is little chance of them taking over everything we do. Instead, perhaps, a reality in which many of our current jobs are adapted or possibly no longer needed is more viable. This is something to embrace, not to fear, it means more menial tasks such as data processing and repetitive actions could be adopted by AIs, leaving humans to be far more strategic in their working lives and take roles that require more emotional intelligence, human instinct and conscious thought.

Example 2:

Will AI take over human jobs?
The question of whether AI will take over human jobs is a topic of significant debate and speculation. While AI has undoubtedly made remarkable advancements in recent years, there are differing viewpoints on the extent to which it will impact the job market. Some argue that AI will indeed replace a substantial number of jobs, as it can automate repetitive and routine tasks more efficiently and accurately than humans. Industries such as manufacturing, transportation, and customer service are already witnessing the integration of AI technologies, resulting in changes to employment patterns. However, there are also those who contend that AI will complement human labor rather than replace it entirely. They argue that AI will create new job opportunities, as it can augment human capabilities and provide innovative solutions. Additionally, jobs that require creativity, emotional intelligence, critical thinking, and complex problem-solving are believed to be less susceptible to AI takeover. Ultimately, the future impact of AI on human jobs remains uncertain, and it is crucial to adapt to the evolving technological landscape while exploring strategies to ensure a harmonious coexistence between AI and human labor.

Right now, it is often easy to tell when AI has produced content as it is usually centred on fact, not opinion. In a recent BBC Sounds radio documentary, A Documentary: By ChatGPT, presenter Lara Lewington used ChatGPT to help write and produce a programme about the software. While it provided useful information and a starting point for scripts, it became obvious that the tone and the way the information was presented, was far different to both the presenter and the outlet's usual style and that actually, if AI was solely used to create the programme, it wouldn't be very engaging for the end listener.



Answer: Paragraph 1 was human-created

AI in the Defence and Security Industry

While AI has the power to augment our daily lives – helping to plan excursions, write basic content and skill-up at pace – the real power of AI can be seen in industrial and commercial applications. Large language models, algorithms that use deep learning techniques to process massively large data sets, are changing the way many industries operate. In an instant, there is a possibility to process all of the learnings that have come before and identify new ways to innovate and move forward.

In December 2020, the US Air Force used AI as a co-pilot and 'mission commander' on a simulated military mission for the first time. The algorithm assumed full control over sensor employment and tactical navigation, while its human teammate piloted the aircraft. This was a significant step in making AI more of a reality in the complex air domain, where computers and systems are hard to update and innovate with their highly secure and locked-down systems.

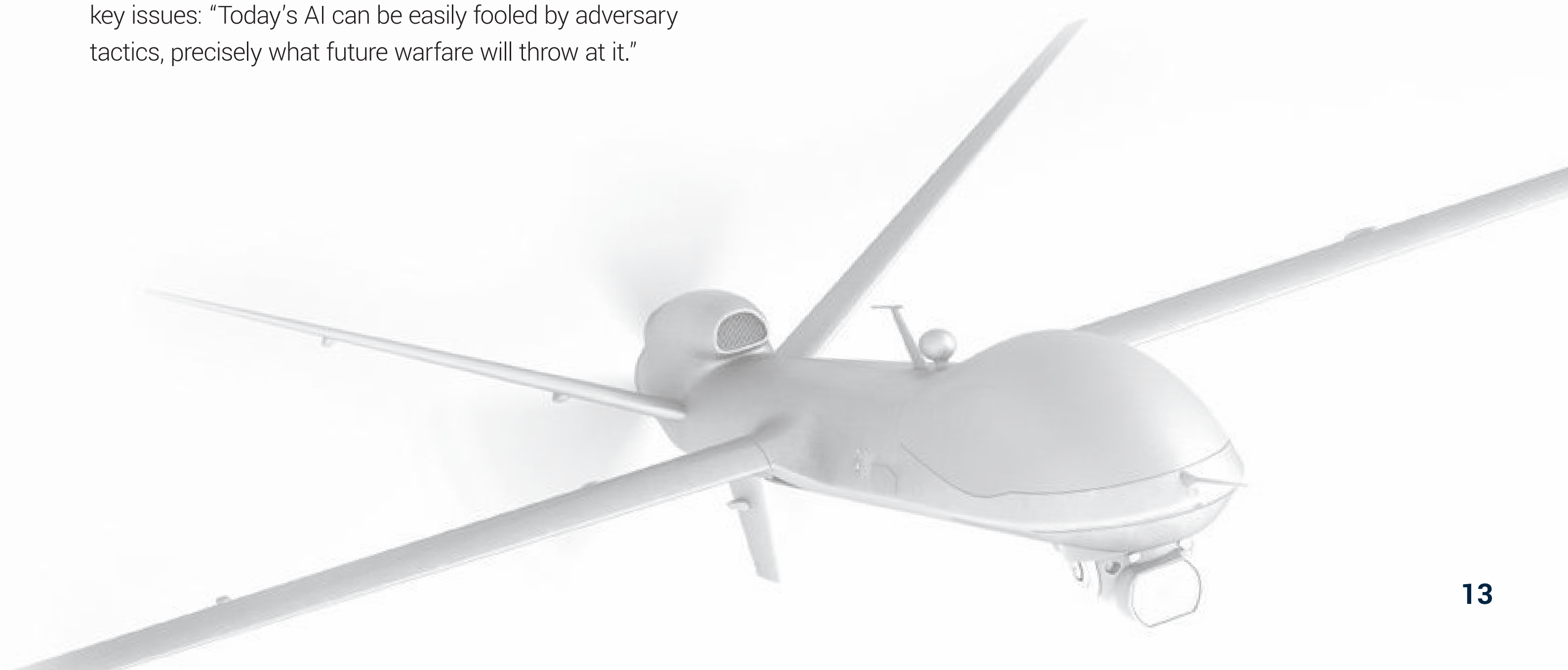
The team behind the Air Force project blended development, Security and operations using a more agile approach to information technology and producing higher-quality code faster and more continuously. The algorithm design allows operators to choose what AI will and won't do and where it pushes the boundaries of operational risk.

So, if this simulated mission went successfully, why can't we rollout AI more widely in Defence? Dr Will Roper, Assistant Secretary of the U.S. Air Force for Acquisition, Technology and Logistics and lead for this project highlights a few of the key issues: "Today's AI can be easily fooled by adversary tactics, precisely what future warfare will throw at it."

Writing in Popular Mechanics, he also highlighted one of the key learnings the industry needs to work through over the coming years: "As we complete our first generation of AI, we must also work on algorithmic stealth and countermeasures to defeat it. Though likely as invisible to human pilots as radar beams and jammer strobes, they'll need similar instincts for them—as well as how to fly with and against first-generation AI—as we invent the next. Algorithmic warfare has begun."

AI's impact on how decisions are informed, made and implemented will be profound. By processing vastly more data at speeds that defy current human-based processes, AI can improve understanding of the operating environment and reduce the cognitive load on decision-makers.
This enables application in Defence and Security from surveillance and reconnaissance to cyber Security, robotics and autonomy, platform management and maintenance, combat and even weapon systems. However, the industry must simultaneously work to develop counter measures to thwart adversaries and recognise misinformation, such as deep fakes – a synthetic media that has been created using existing data and mimics a real person.

As the technology becomes more prolific, there is certainly a call for more governance around safe and ethical practice in AI. The UK Ministry of Defence has established the Defence Artificial Intelligence Strategy as well as setting up multiple working groups and policy papers. We are also seeing industry-led movements in the US that call for tighter regulation and audit for AI companies. This area is where we are likely to see the biggest changes worldwide over the next year.



So, will AI replace humans and lead the Defence industry in future?

Overall, AI has become an increasingly important and pervasive technology over the past two decades, with applications ranging from speech recognition and recommendation systems to self-driving cars and medical diagnosis. These advances have made AI more powerful, accurate, and accessible than ever before, enabling a wide range of applications and use cases across many industries.

As the BBC ChatGPT Documentary concluded, it is likely that AIs will largely be used to augment human activity, not replace humans (at least for now). If used correctly, AI can help to reduce the amount of time humans spend on menial tasks and allow us to grow and focus on more strategic or innovative paths. We should be embracing its potential rather than fearing it or trying to resist it.

In the Defence industry specifically, AI is fast becoming a core part of our national Defence strategy. Global military and intelligence agencies are embracing the new technology and augmenting existing workforces. These applications are generally focused around summarising and processing large amounts to data for better decision making, shortening processing times and providing a better understanding of the operational environment.

It is extremely unlikely that AI will be given complete control in this environment, unless for low-risk, low-trust applications. For now, at least, it is important to keep a human in the loop and embrace AI as a core part of our wider operational team, not our leader.

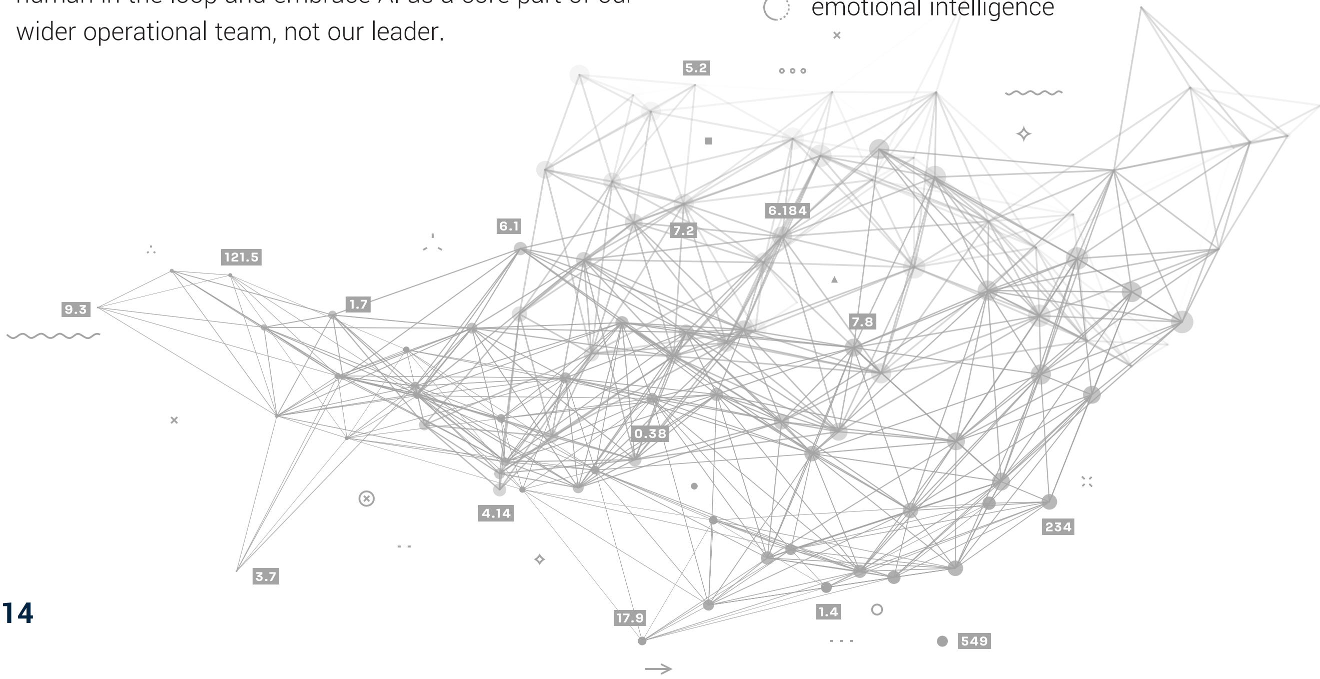
In a recent study by Accenture, **84%** of business executives believe they need to use AI to achieve their growth objectives. However, **76%** acknowledge struggling with how to scale AI across their business.

Pros of using AI

- Good at detail-orientated jobs
- Reduction of time for data-heavy tasks
- Saves labour / increases productivity
- Delivers consistent results
- Can improve customer satisfaction – personalisation
- Always available

Cons of using AI

- Can be expensive, particularly if not off-the-shelf
- Often requires deep technical expertise to manage
- Limited supply of skilled workers to build and manage systems
- Reflects biases of training data
- Lack of ability to generalise
- While improving, still lacks emotional intelligence



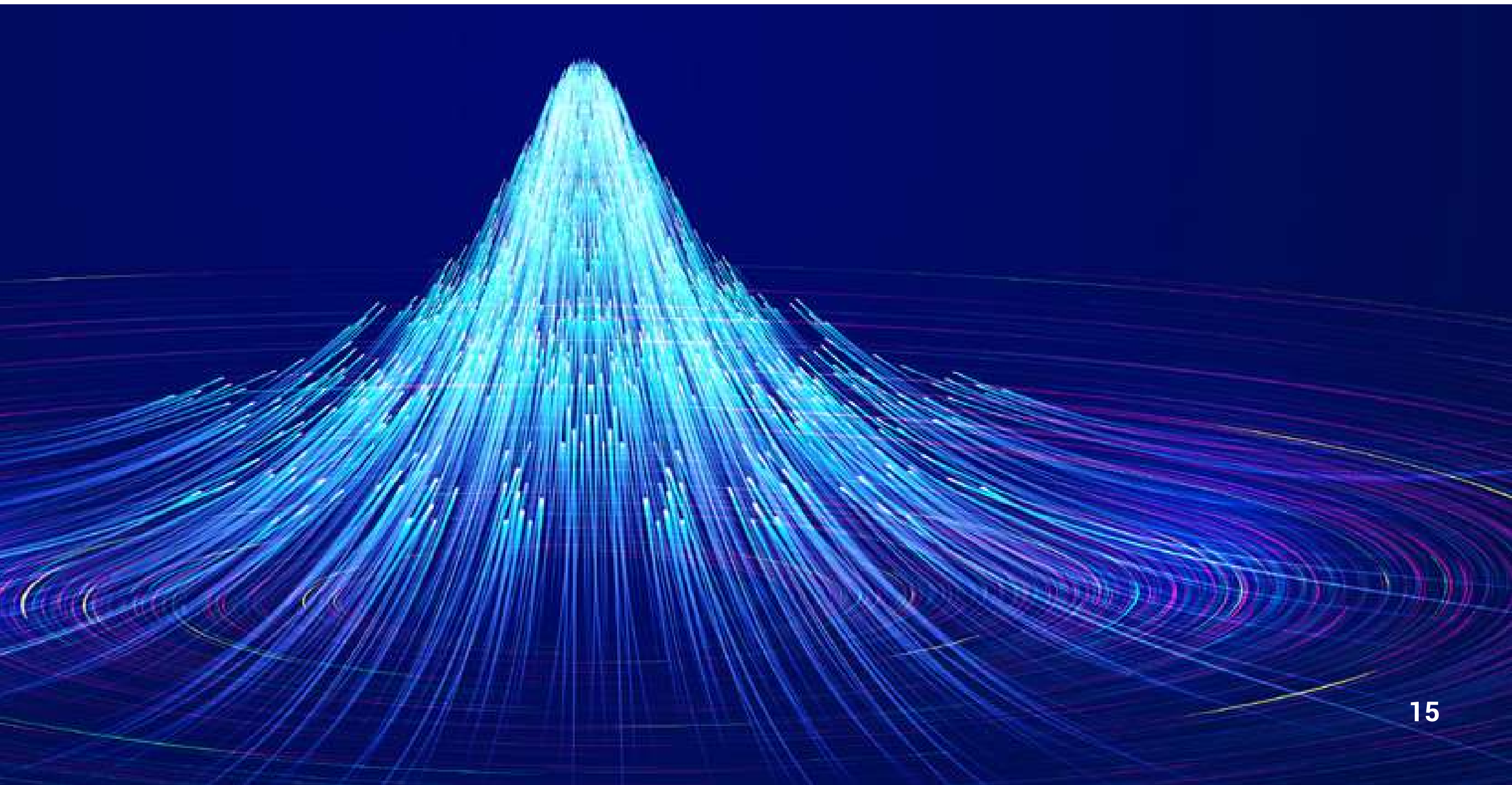
AI

DEEP DIVE

A System of Systems: **How the convergence of Artificial Intelligence (AI) platforms can deliver true capability**

AI, as a tool, presents limitless opportunities to make everything simply 'better'. From self-driving cars to chatbot assistants, AI systems are starting to shape how the world works. But as mentioned earlier, the potential of use cases that can be delivered from AI remains largely untapped.

Searching for an answer in that vein has led many researchers to conclude that a convergence of AI platforms is where their true potential lies. AI may not function wholly as a stand-alone system that can deliver the truly mind-bending capabilities it is supposed to. In the future, AI can function as a connecting thread combining multiple platforms to deliver unmatched functionality.



This would function more like a system of systems that takes up the best part of each platform to give optimised results, using the classic concept of reusability and continuous improvement.

"The whole is greater than the sum of its parts" is a phrase we've all heard before, usually used to articulate the benefits of collaboration and teamwork. This concept of synergy has been understood for centuries, but it is now something we can use to capture the power of collaboration in Artificial Intelligence.

Combining constituent parts to create something more powerful and reliable is something we see across all aspects of AI systems, from the algorithms that help the AI learn, to the approaches used to interpret data. Even distinct AI systems can be combined to create a larger, more complex intelligence system. These components can be reused and improved continuously as the various interconnecting platforms utilise them.

This article attempts to unravel the secrets behind these collaborations, assessing the benefits and risks and providing real-world examples relevant to the Defence and Security world.

Not every AI is made equal

Understanding the forms of AI in the market

While talking about the various constituents that could synergise into an AI platform, it is necessary to understand that AI exists in more than one form. AI systems often comprise basic building blocks such as the AI approaches used, the specific implementation model, the datasets used to train the models, the supporting infrastructure and other relevant tools and applications.

AI Approach

An AI approach refers to the method used to teach computers to perform intelligent tasks. Think of it as a set of tools or strategies that enable machines to mimic human-like intelligence. These approaches involve algorithms and processes designed to process data, learn from it, and make informed decisions or predictions. Two major approaches to AI are machine learning and pre-programmed, with most modern AI systems using a machine learning approach.

AI Approach example: Machine Learning

Machine learning involves training computers to learn from data and make predictions or decisions without being explicitly programmed. An example of this approach in action is a spam email filter. The machine learning approach is used to develop an algorithm that can analyse the content and patterns of emails. By training the algorithm on a large dataset of known spam and non-spam emails, it learns to distinguish between the two. This approach enables the computer to calibrate itself against spam emails, allowing it to detect them and automatically filter such messages.

AI Model

An AI model is a specific implementation or application of an AI approach. It's like a blueprint or a recipe that guides a computer system in solving a particular problem or performing a specific task. AI models are built by training them on large amounts of data and allowing them to learn patterns and relationships within that data. Once trained, the model can take in new inputs and provide outputs or predictions based on its learned knowledge. For example, a model trained to recognise images of vehicles will learn what a vehicle commonly looks like, and can use this training to analyse new images and determine whether they contain a vehicle or not, even if it has never seen that specific vehicle or model before.

AI Model example: Image Recognition

In the context of image recognition, an example of an AI model is the "Inception-v3 model". This model has been trained on a massive dataset of images and can recognise thousands of different objects and concepts within images. For instance, if you provide an image to the Inception-v3 model, it can analyse the visual features and predict the objects present, such as identifying a person, a tree, or a car.

AI System

An AI system is a complete setup or infrastructure incorporating one or more AI models to perform a specific task or solve a complex problem. It encompasses the hardware, software, data, and algorithms required to enable the AI models to function effectively. An AI system may involve multiple components, such as data pre-processing, model training, and deployment mechanisms. It provides the environment for the AI models to operate, making decisions or generating insights based on the input data it receives.

AI System example: Autonomous Driving System

Autonomous Driving Systems combine various AI models, such as computer vision models for object detection and tracking, natural language processing models for understanding voice commands, and decision-making models for navigation and collision avoidance. The AI system takes inputs from sensors, cameras, and other sources, processes the data using the AI models, and generates appropriate responses to control the vehicle, enabling it to drive autonomously.

In summary, an AI approach is a general approach or method used to teach computers to be intelligent, an AI model is a specific implementation of an AI approach for solving a particular problem, and an AI system is a complete setup that incorporates AI models to perform tasks within a specific environment.

A powerful combination

AI Convergence: merging otherwise independent AI elements, forming one complete solution.

AI Convergence refers to integrating or combining different branches or subfields of artificial intelligence to create more advanced and powerful AI systems. It involves uniting various AI approaches, models, or systems previously developed independently and leveraging their synergies to achieve enhanced capabilities.

One example of AI Convergence is the application of machine learning and natural language processing (NLP) approaches in virtual assistants like Amazon's Alexa or Apple's Siri. These virtual assistants utilise machine learning algorithms and NLP techniques to understand spoken or written language, extract relevant information, process data and generate intelligent, human-like responses.

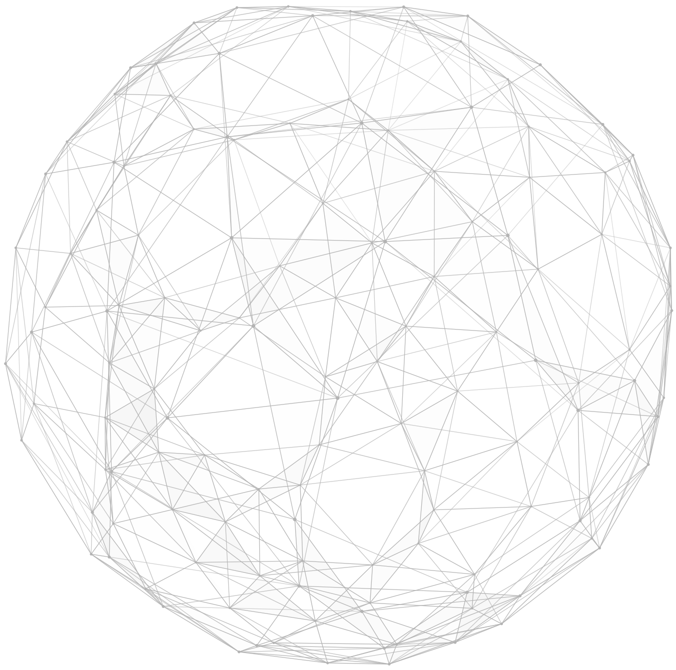
This convergence of machine learning and NLP showcases the power of combining different AI approaches to create more sophisticated and useful AI systems that can understand and interact with humans naturally.

AIoT

Another powerful use case that convergence presents is the Artificial Intelligence of Things (AIoT), which integrates the Internet of Things with powerful AI models. Adding AI to IoT has been proven to be a mutually beneficial application model for both disciplines. The IoT network benefits from quicker decisions and improved analysis and performance. And IoT helps advance AI capabilities through network, connectivity, and signalling data exchange. This dramatically increases the amount of data and throughput available due to the number of devices in the system. AI and IoT convergence systems are already used in many sectors, especially being put into good use in smart homes, manufacturing, health monitoring, sales and the automotive industry.

AI and Quantum Computing

This upcoming area of convergence promises multiple ways to strengthen and improve economies and communication systems across the world. Both these disciplines stand to benefit from each other in some feedback loop. Quantum computers require novel hardware and algorithms to function, which can be derived with the help of AI-based learning models. The quantum machines thus designed and developed can be of immense help to further improve the efficacy of AI systems. The importance of the linkage between AI and Quantum computing was illustrated in the UK Government Spring Budget Speech where additional funding for both disciplines was announced.



AI and business management systems

AI presents limitless opportunities in the business space and operational management of any type of organisation. From workflow automation to making strategic recommendations, AI can greatly help optimise business processes, sales management, targeted marketing, and more when used in conjunction with enterprise software.

An interesting example in the business area would be the combination of AI in category management systems. AI can be used to select the best supplier based on certain factors and help with sourcing by identifying the best options for businesses relevant to price, quality, timing and more.

AI can be a boon in planning for new product designs with its predictive analytics on market conditions, user behaviour and expectations. It can help businesses analyse and optimise their spending, allocate budgets efficiently, and perform optimised resource allocation.

Hiring activities, onboarding, and personnel performance evaluation can also be enhanced with the help of AI-based tools and resource management systems. Thus, AI as a common element can be used wisely to optimise over all aspects of running a business or any organisation. However, care needs to be taken in ensuring that any such deployed systems do not exhibit the biases that may be found in historical training data.

AI applications and use cases in Defence and Security

The Defence and Security industry has significantly impacted the development of most of our ground-breaking technologies, including AI; the internet as we know it today would not have been made possible without the initial research by the US Defence Department, for example. Akin to many of the commercial benefits highlighted, Defence systems stand to benefit greatly from these new technologies too.

As more governments invest, AI applications are set to achieve wide-scale adoption within Defence systems. Countries like China, the USA, and Russia are aggressively pursuing military applications of AI and robotics. As tensions continue to rise, nation states will be keen to develop and exploit AI tools to get ahead and stay ahead of their adversaries.

This is especially true where military tactics are concerned, as many countries increasingly rely on AI-based technologies to improve their intelligence systems, surveillance, cyber Security, logistics, reconnaissance and health support.

Some of the AI domains that are increasingly used in military projects include:

- Intelligence analysis
- Surveillance and threat detection
- Cyber Security, including anomalous behaviour and event detection
- Supply chain management
- Drone swarms and autonomous systems
- AI-based personalised training combat simulations
- Target identification

In all these use cases, AI is not a stand-alone system but a force multiplier that can transform and enhance the desired results. In that sense, it can also be considered to be a general-purpose technology that can be retrofitted across a wide range of platforms and systems to suit the specific application in consideration. AI is thus comparable to how fuels are used to power a wide range of mechanical systems. The global AI market relevant to Defence was estimated to be $7.7 billion USD in 2018 and is expected to grow to $26.52 billion by 2025.

Converged AI in Defence & Security applications

Intelligence Analysis

AI convergence combines various AI approaches like natural language processing, machine learning, and computer vision to analyse vast amounts of data and extract valuable insights. Integration of these AI approaches enable processing of a dramatically higher throughput of information, and increased speed of response. It allows intelligence analysts to process and analyse diverse data sources such as text documents, images, videos, and social media feeds to detect patterns, identify threats, and generate actionable intelligence.

Surveillance and Threat Detection

AI convergence is utilised in developing advanced surveillance and threat detection systems. These systems integrate computer vision, sensor technologies, machine learning, and data analytics to monitor and analyse large-scale environments. For instance, intelligent video analytics systems can combine computer vision techniques with machine learning algorithms to automatically detect and track suspicious activities, objects, or individuals in surveillance footage, enhancing situational awareness and aiding Security personnel.

Cyber Security

The invisible shield protecting a nation's cyberspace is as important as physical border forces. In a highly digital world, cyberspace needs to be protected from malicious attacks to keep the information systems of a nation safe and secure. Critical national infrastructure is a key target for digital aggressors, and protecting that has become a matter of national Security. Loss of sensitive data can lead to several issues, and AI can help Security systems prevent data breaches proactively.

In cyber Security, AI convergence detects and responds to various threats. It combines machine learning, anomaly detection, and behavioural analysis techniques to identify and prevent cyber-attacks. By integrating different AI models and algorithms, Security systems can analyse network traffic, identify unusual patterns or behaviours, and detect potential cyber threats or intrusions in real time, before they cause serious damage.

Intrusion detection is one area of cyber Security that has improved greatly with the help of AI systems. In combination with available network traffic data, AI systems can quickly analyse traffic, detect malicious entry attempts and block them proactively. AI can also be used to gauge the impact of any hacking attack and find better ways to restore systems.

Cyber Security can benefit from AI models such as data classification, clustering, recommendations, predictive forecasting and possibility synthesis. Combining all these models in the right way can help build strong Security systems that are fast, proactive and efficient in blocking threats.

AI approaches can also be applied in simulated penetration testing, where sandboxed network systems can be tested against possible attacks and thus help strengthen real systems better. There are several other ways in which AI can be used in cyberspace. Examples of this include:

- Continuous improvement and learning
- Identify new threats
- Dealing with large amounts of data
- Vulnerability management
- Bot battles

AI applications are already finding great use in cyber Security apps that specialise in risk prediction, malware detection, authentication, spam filtering, password protection, incident response, identity and access management and more.

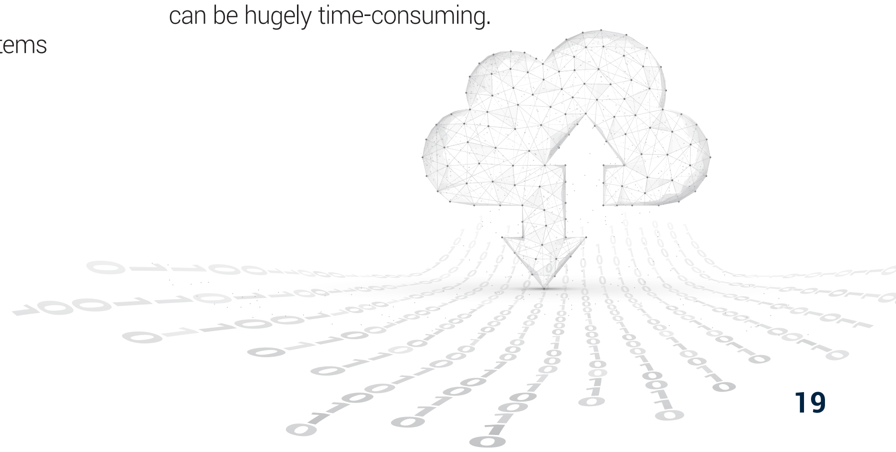
Supply chain management

Supplier fraud can be a big issue with military projects. AI and ML-based Security systems and fraud detection systems can be used to detect suspicious transactions and alert the authorities at the right time. It can also help analyse the demand, supply chain management, contractor analysis, and bid management.

Drone Swarms and Autonomous Systems

Swarm intelligence or AI-powered drone systems have been an interesting development in recent years. These swarms of drones have multiple uses besides surveillance. They can be used for simulations, and training programmes, gather a huge amount of geospatial data in a short time and even have the ability to act independently according to environmental conditions thanks to AI. AI-powered drone swarms are designed to mimic the natural behaviour of insect swarms. These drones can communicate among themselves about parameters like potential targets, obstacles, distance, and direction. They work towards a collective intelligence that can greatly help apply military objectives in a real-world scenario.

Besides surveillance, drones can also be used to resupply remote outposts where getting a regular crewed vehicle can be hugely time-consuming.



Combat Simulation

Simulation software for military training is a known tool used by several military agencies, especially the US Army. These software programs are comparable to a video game experience except that they are more sophisticated and present real-world scenarios under which to train combat specialists. These simulations combine systems engineering, software engineering and AI models to build complex war game scenarios with room for multiple strategies and real-life situations. They try to mimic real-life mission scenarios and possible threats so that soldiers are trained to deal with these scenarios before getting into a real-life situation. Simulations provide a safe and cost effective environment to train personnel without having to endanger anyone with the presence of real weapons. The weapon systems are made to be as realistic as possible. Situations are presented as they would be in a real-life mission, giving soldiers a taste of how it feels to make important decisions in stressful situations.

A huge advantage of using AI-based combat simulation is that it can be personalised. Personalised training programs allow for better assessments of the soldier's skill levels and help tailor the training program to be more productive in future sessions. AI-based combat simulations are also a huge money and time saver given how easy it can be to set up training with software simulation compared to a real-world simulation environment.

Target identification

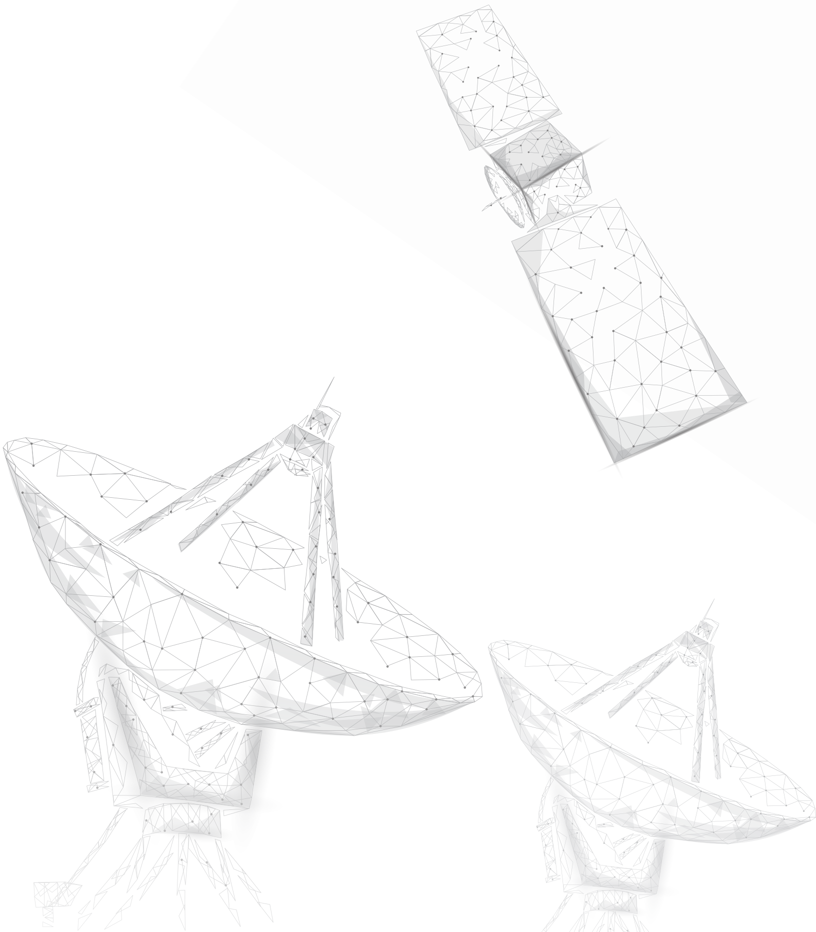
While modern surveillance systems make it easy to collect visual information, making sense of such data still largely depends on human personnel. With AI, such time-consuming tasks of target recognition can be sped up by a large factor. AI can thus also greatly help to monitor remote outposts and uncrewed facilities. It can help with monitoring threats, provide much-needed situational awareness, alerts on intruder entries and more. Drones and satellite-based systems can also be integrated into this overall monitoring system to provide wider coverage. This enables militaries to ensure timely response and border monitoring and increase the overall safety of their combat participants.

Systems combining the power of radar, optics, and mathematical models can be used to predict how a target moves, its behaviour pattern and more. This extra information would help to predict and pinpoint the attacks and ensure minimal casualty otherwise.

More to unlock?

The examples above highlight how AI convergence offers a way to unlock the full potential of AI within the Defence and Security industry. It can enhance intelligence analysis, develop autonomous systems, strengthen cyberSecurity, and improve surveillance and threat detection capabilities. Integrating multiple AI approaches and models enables more robust and efficient solutions to address complex challenges in these domains.

As has been demonstrated in recent months and years, AI is a field experiencing considerable and rapid growth and development. As we continue to explore and embrace the possibilities of AI convergence, we can expect to witness remarkable advancements and transformations within not only Defence, but other industries too – ultimately shaping the future of how we live and interact with technology.



AI

DEEP DIVE

Assuring AI

Earlier this year, a letter issued by the Future of Life Institute, called for an immediate six-month pause on the training of all Artificial (AI) systems "more powerful than GPT-4". The reason? "Profound risks to society and humanity," according to the signatories, which included high-profile individuals such as Elon Musk (CEO of SpaceX, Tesla & Twitter) and Steve Wozniak (co-founder of Apple). Whilst some have suggested their motivation may be as much a desire to catch up, it nevertheless echoes similar real-world concerns, not least from Professor Yoshua Bengio, one of the so-called "godfathers" of AI.

AI is becoming so advanced that a chat system like GPT-4 can have an argument with you. And if something can have an argument with you, then there is a temptation to treat it like a human being – even if, under the hood, it does not think like a human being at all.

Paradoxically, the more confidence and trust we put in AI, the more reason we need to assure it. This holds especially true for Defence organisations who are increasingly seeking to explore the potential use of AI enabled components in mission and safety critical systems. Yet AI technology's behaviour is neither transparent nor predictable. This creates technical testing/assurance challenges for both business and government organisations seeking to implement it to gain an operational advantage over competitors or potential adversaries.

Why do organisations need to assure AI?

Put simply AI Assurance helps organisations better understand technical risk (i.e. will it work), operational risks (i.e. Safety and Security), and to give them the means to demonstrate compliance with national and international laws, other legislation with pan-national impact (i.e. laws made by one country/body impacting organisations in other countries), existing regulations (e.g. aviation safety) and emerging technology-specific regulation for AI. It should also help organisations demonstrate compliance with moral, ethical and humanitarian principles and other non-statutory guidance, such as data ethics principles.

Technical Risks - Organisations obviously need to prove to themselves that an AI model is technically capable of doing what its developers claim. Commercial imperatives often encourage the adoption of off-the-shelf solutions, yet vendors of proprietary, "black box" AI solutions may give the buyer very little information on how these have been developed in practice. As systems become increasingly interconnected, special care needs to be taken if one AI model feeds another.

Security Risks - AI technologies are vulnerable to a range of well-known adversarial attack methods, such as poisoning of training data, as well as offensive Cyber and Electro-Magnetic Activities (CEMA) and other techniques which manipulate input signals to effectively misdirect the AI models. In Defence and Security any loss – be it physical (e.g. loss of an autonomous asset with an embedded AI component) and/or virtual (e.g. AI model exfiltration through a cyber "back-door") – can have significant operational implications. AI-enabled projects also typically draw on a limited number of openly-published model architectures, using samples of the client's data to adapt the model to the problem at hand. This limited 'gene pool' of algorithms might present operational risks if, for example, one method of attack might work against multiple models.

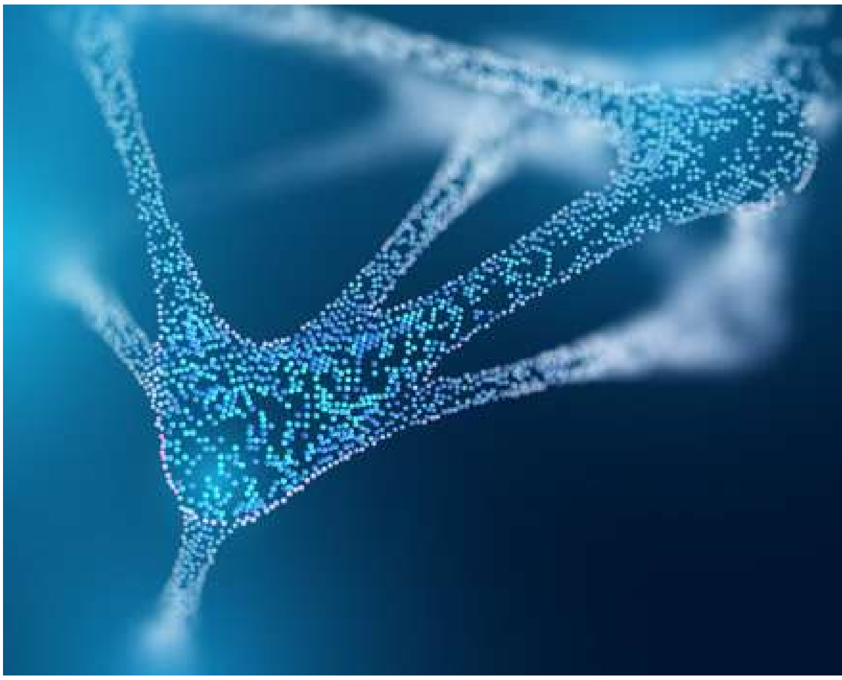
Compliance Risks - Organisations adopting AI need to be able to demonstrate compliance with both statutory and regulatory requirements. Whilst the adoption of AI is running ahead of government regulation, governments around the globe are catching up fast, and many are now looking very closely at how this comparatively new technology should be regulated. Until AI-specific laws are introduced, organisations will continue to need to navigate the non-technology specific legal frameworks and general laws (e.g. data protection and privacy, consumer law, discrimination law, copyright law etc.), sector-specific laws and regulations (e.g. motor vehicle, therapeutic goods etc.) in each jurisdiction. For Defence, particularly where AI is being used in autonomous systems, risks need to be considered in the context of the Law of Armed Conflict/International Humanitarian Law.

International Approaches to AI Regulation - With the recent talk about an international regulator for AI (akin to the International Atomic Energy Agency), with the UK Prime Minister keen to have this based in London, it is worth taking a moment to look briefly at international approaches to AI regulation. The OECD publishes an excellent resource on this[1]. There appear to be two main schools of thought on AI regulation, either principles-led or more prescriptive, with those that are principles-led being more reliant on legal systems and the courts to establish case precedent. The U.S. federal government's approach is risk-based, sector specific, and highly distributed across federal agencies. The UK is also considering a decentralised[2] approach, with each existing regulator being responsible for AI regulation within their own areas of oversight. Despite being one of the first countries in the world to publish AI Ethics Principles, there is still no AI-specific legislation in place in Australia. In India the IT and Telecom Minister Ashwini Vaishnaw said recently that "the government is not considering bringing a law or regulating the growth of artificial intelligence in the country". On the other hand, the EU and Brazil are both considering a more centralised approaches[3] with new regulatory bodies. Brazil recently announced that the primary aim of it's new AI law is to grant individuals significant rights and place specific obligations on companies that develop or use AI technology (AI supplier or operator).

1. The OECD "State of Implementation of the OECD AI Principles: Insights from National AI Policies" report looks at how countries are implementing the five recommendations to governments contained in the OECD AI Principles and examines emerging trends on AI policy.
2. UK AI Regulation - AI regulation: a pro-innovation approach - GOV.UK (www.gov.uk)
3. The proposed EU AI Act – EUR-Lex - 52021PC0206 - EN - EUR-Lex (europa.eu)

So how do you assure AI?

The best AI Assurance regimes are both Compliance and Risk based. As an activity, AI Assurance begins early in programme design, runs throughout initial model development and then continues into live service, until final safe disposal of the model and supporting data. Emerging best practice is that as an activity, this sits within the organisation's existing project and technical assurance regimes, as the AI component will often be just one element of a much wider system. Assurance effort also needs to be proportionate to the use case, and be based upon the commissioning organisation's appetite/tolerance for risk across a wide range of factors (for example functional performance, Security, resilience, safety, ethics and trust). However, this sustained assurance effort has clear resource implications and needs to be properly planned and budgeted.



AI assurance is best delivered through two parallel work strands:

Governance, Risk and Compliance (GRC), which establishes and executes the management controls for the programme and implements suitable tools to capture dependencies, assumptions, issues and risks/mitigations, within the organisations overall approach to technical and project assurance, so that all risks and their mitigations can be presented cogently for decisions by the specialist regulators (e.g. Safety and Security), so that they in turn may issue certificates of clearance for use. Good AI Assurance regimes should also consider risks/barriers to adoption by end users and decision makers, such as explainability, trust factors, training needs and user–interface development. These are all key to operationalising AI at pace.

Test, Evaluation Validation and Verification (TEVV), which carries out laboratory-based technical investigations and, if necessary, field trials to prove technically that the AI will do what it's developers, claim in the right operational context. TEVV surfaces foreseeable risks in data science (such as model performance and robustness related risks), Security (i.e. physical, cyber and electromagnetic activity related risks), trust and adoption, integration and safety (including policy enforcement controls that limit the AI model's ability to harm by constraining/limiting permissible model outputs) and sustainability.

Data science risks are determined using a broad mix of data science, data engineering, Machine Learning Operations (MLOps) and IT expertise. A test harness enables test data preparation, data transformations (to add bias, noise, or simulate particular environmental conditions), AI Model testing and the definition of metrics, which in turn are applied to model outputs under test.

For test data preparation, given the risks of bias and false learning, a "good enough" data set is, in fact, not good enough. AI models should be trained, tested and assured on the best available real-world data appropriate to the use case. If not possible as the real data is sensitive or classified, then synthetic data can be generated as a substitute. If real world data is being used, this needs careful management to avoid inadvertent security breaches or compliance failures – particularly of privacy laws if personal data is being used.

Assuring the future

Any organisation thinking about implementing AI technologies as part of a system, irrespective of whether it is in back office enabling processes or in mission critical systems, need to think about AI Assurance and do so early. It needs to be planned and budgeted for through life. AI Assurance will need some capital investment and an operating budget – as a rough heuristic, testing and assurance should be 30% of the overall AI component's budget.

Many organisations have or are developing ethical AI principles and frameworks – of which there are now many. Each of these put slightly different emphases on issues such as fairness, moral and ethical use of AI, data ethics, citizen privacy, citizen redress or Security. There also many useful AI frameworks published by non-governmental bodies[4] and commercial organisations, which offer useful "tick-box" approaches to compliance (i.e. "have you considered 'X'?"). If your organisation doesn't yet have an approach to responsible and ethical AI implementation, these are a good starting point..

Emerging best practice in AI Assurance

The science and practice of AI assurance is still immature but we believe these 6 steps will help projects get it right from Day 1:

- **Step 1 – Implement an AI Risk Management Framework.** Early in Programme/Project Design, leaders should implement a "top-down" AI Risk Management Framework[5] appropriate to the regulatory environment for the use case.

- **Step 2 – Determine the Organisation's Risk Appetite and Set Clear Priorities.** Assurance effort should be proportionate to the organisation's appetite/tolerance to risk and not every AI project will need every possible risk factor to be exhaustively tested. This should be discussed early in programme design.

- **Step 3 – Adopt an Agile Approach to Assurance.** Early assurance testing can also help identify AI vulnerabilities or design flaws and enable prompt remediation, or even project termination, under a "fail fast" approach. An Assurance Backlog built and maintained in parallel to the Product Backlog will help synchronise assurance and capability development activities.

- **Step 4 – Take a Multi-Disciplinary Approach.** Assuring AI needs new types of expertise to be brought into the assurance process at different points in project delivery, including data scientists, ethicists, human factors experts, Cyber, Adversarial AI and CEMA assurance experts, safety experts, Security experts, trial experts and data engineers to name but a few.

- **Step 5 – Implement Strict Configuration Control over AI Models and Training/Test Data.** QinetiQ advocates the use of model Cards to bring configuration control to AI model development and also into live service, capturing changes made under MLOps. The model card is simply a record of the version of the AI algorithm in use, the dataset it has been trained upon, and the separate data set it has been tested against by the developer. This helps TEVV experts assure the algorithm's "learning" against its original training data and to determine the validity of the data. It also documents assurance testing and the datasets used for this. Having a standard approach to model cards and enabling tooling are highly recommended.

- **Step 6 – Invest in Data You Can Trust.** Potentially very large quantities of data will be needed for initial model training, with yet more required developer testing and assurance testing. Projects need to understand the provenance of their data and all data should be checked to ensure it has not already been poisoned. Data leakage risks can also be controlled by curating "golden" datasets which are kept exclusively for evaluation purposes.

4. For example the UK Centre for Data Ethics and Innovation (CDEI) AI Assurance Guide Beta.

5. US National Institute for Standards and Technology's (NIST) AI Risk Management Framework published in Jan 2023 is a good example.

DEEP DIVE

Advanced materials and their future in Defence

The extraordinary properties of advanced materials could transform our world and life as we know it. They may also prove to be one of the most significant developments towards creating a more sustainable planet and could provide the means for making interplanetary travel a reality. For the military, they are a game-changer, with the potential to revolutionise Defence operations and drive unprecedented change to the dynamics of the battlefield in the years to come.

The golden age of materials science

We are currently in what many would describe as a 'Golden Age' for materials science with the advent of new, high performance materials, with their exotic attributes and almost supernatural capabilities. Innovation continues to reach new heights with the creation of materials whose characteristics may appear 'otherworldly' such as their ability to self-heal or to enable invisibility.

As military systems become ever more complex, so are the materials required to build them. Advanced materials are therefore an essential part of future Defence and Security capabilities around the world. Recent developments have shown that the properties and characteristics of advanced materials and their versatility could potentially be a game changer for the Defence sector with no end to the possibilities they could bring in creating state-of-the-art Defence and protection systems. As a result, they have sparked considerable interest as their use has the potential to significantly shape future operational effectiveness in military missions.

By better understanding and manipulating their properties, advanced materials can improve mission survivability and increase the agility of forces during live operations. They may also make it possible for existing technologies and equipment to be upgraded rather than redeveloped. Many of the major land, sea and air platforms currently in service are not expected to be retired for another two to three decades, which means they will have to be modernised with new materials. The ability to upgrade platforms will save time and money, but will also reduce training requirements on new assets and extend their lifespan. The transformative abilities of advanced materials and the manufacturing behind them are therefore critical enablers when considering both the importance of reducing cost to deliver customer requirements and in maximising performance to deliver operational superiority.

The significance of graphene

The isolation of graphene by two scientists at Manchester University in 2004 attracted a Nobel Prize. Its combined properties placed graphene, an allotrope of carbon, in a league of its own – a transparent structure that is many times stronger than steel, yet flexible and lightweight and a good conductor of electricity and heat - its applications could be endless. But the single feature of graphene that sparked such a tidal wave of interest was extraordinary in itself – a million times thinner than a single human hair - it became the world's first 2D material.

The excitement that this discovery generated amongst academics and scientists served to place graphene firmly in the spotlight. In 2013, Europe set up its biggest ever research initiative, creating the Graphene Flagship with a budget of £1bn and in 2015, Manchester University founded the National Graphene Institute (NGI), an epicentre of graphene development. This would enable researchers from across industry and academia to collaborate globally on graphene applications. The global graphene market is projected to reach $1,479m by 2025, but possibly of more significance than graphene itself, is the role it has played in the discovery and synthesis of an entirely new class of materials.

Engineering the gap and the creation of TMDs

Whilst the transformational impact within the materials sector that graphene underpins might indeed be vast, despite the hullabaloo surrounding it, graphene has a number of significant drawbacks. In addition to being costly and time consuming to produce, meaning that mass production of high quality and defect-free graphene is problematic, it does not have what is called an 'electronic bandgap'. This 'lack of bandgap' means that its application in semiconductors such as transistors and other electronic devices is limited, but it is this limitation that gave rise in recent years to a set of more versatile new materials called Transition Metal Dichalcogenides (TMDs).

TMDs combine a transition metal atom with a chalcogen[7] atom, resulting in a 2D material with similar properties to graphene whilst overcoming the problem of the lack of bandgap. They have additional structural properties to graphene – they are potentially stronger, more flexible and have a higher electron mobility.

7. A chalcogen is an element in group 16 of the periodic table, including oxygen, sulphur and selenium

The significance of 2D materials in Defence

Two-dimensional materials are becoming very popular for research and may have usefulness within a vast arena of military applications, from high-end electronics, sensors and detector systems, to energy harvesting and storage, photonics and optoelectronics as well as protective coatings.

Communication Antenna: A growing area for the use of 2D materials is for communication antennas, such as for satellites, radar, 5G communications and Wi-Fi routers. The combination of communications performance with extreme thinness, flexibility and durability sets a new standard for antenna technology. Owing to the growing bandwidth requirement and need for secure communication, government agencies such as DARPA within the US DoD and NASA are investing extensively in research to develop these antenna.

One example that is gaining attention is a class of 2D materials called MXenes, which are so thin they can be sprayed into place, while providing a strong signal across the 5G bandwidth. MXenes are already proving to be superior in performance to other alternatives including silver ink, carbon nanotubes and graphene and can be screen printed or ink-jet printed onto just about any substrate making them extremely versatile.

It is possible that in the future, surfaces that double as communications antenna could be used on a much larger scale, for example, the creation of coatings or films that can be applied to the surface of military vehicles and aircraft to enhance electromagnetic shielding, reduce or block interference and improve signal quality.

Energy harvesting and wireless energy transfer: Innovative energy harvesting techniques using TMDs could potentially reduce the need for external power sources whilst improving the capabilities of military devices and systems. The excellent light absorption and semiconducting properties of materials such as molybdenum disulphide and tungsten disulphide can be integrated into solar or photovoltaic cells to convert solar energy into electricity and their lightweight, flexible structures make them ideal for wearable applications such as communication devices and navigation systems.

TMDs are being further explored for mechanical, thermal and radio frequency energy harvesting abilities which could reduce logistical burdens and enhance the overall effectiveness of wearable technologies. For example, if integrated into the fabric of military uniforms, they could harvest solar energy or mechanical energy from body motion and convert it into electrical energy to continuously power various electronic components embedded within the clothing or gear.

MIT have developed the first fully flexible device using molybdenum disulphide that can convert energy from Wi-Fi signals into electricity to power electronics. The device is a new form of 'rectenna' that uses a flexible radio frequency antenna to capture electromagnetic waves, including those carrying Wi-Fi, as AC waveforms. The antenna is connected to a device made out of a 2D semiconductor just a few atoms thick which converts the AC signal to a DC voltage (electricity) that could be used to recharge batteries or power electronic circuits.

The potential of wireless energy transfer for military applications is an exciting area of investigation, with researchers seeking to create a 'wireless' energy web. In situations where a weapons platform depends on storing enough liquid fuel to generate power, the introduction of a wireless power transfer network would negate the need for the fuel. The platform would therefore become a conduit receiving power wirelessly rather than requiring a fuel and its container. If researchers could overcome the problem of creating an efficient system to convert energy, this could revolutionise the way in which power is delivered and utilised.

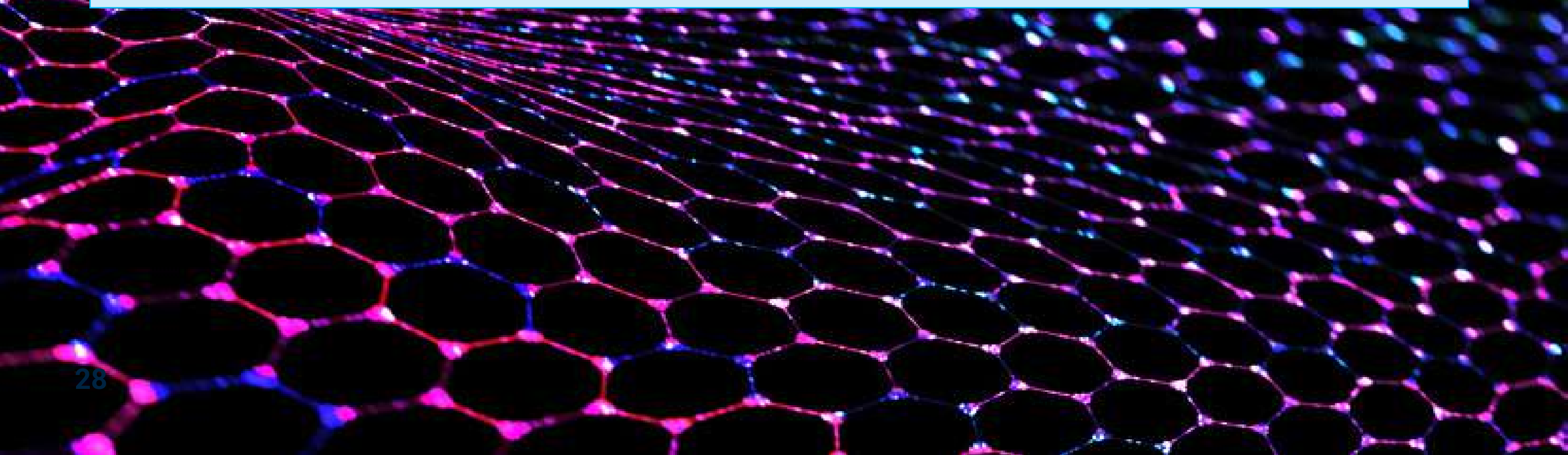
James Baker
CEO of Graphene@Manchester

The curious properties of graphene and the nanoscale ‘club sandwich’ with revolutionary capabilities

“Research breakthroughs from graphene and 2D materials have included many composite projects from polymers to concrete, freestanding graphene membranes and coatings; graphene inks; ink-jet printed electrodes; performance-enhanced batteries using graphene electrodes; and ultra-high sensitivity graphene-based field sensors. Today, discoveries are still being made in this field and the continued interest in graphene investigation has been intriguing. Graphene continues to attract large numbers of researchers and increasing interest from industry on commercial products and applications. With the creation of supply-chains now producing graphene materials at quantity, many new applications are starting to enter the market.

“Over the past 10 years we have seen around 50 start-ups and spin-out companies associated with graphene and several of these new companies are making significant progress in membrane technologies with the securing of investment and production of prototypes. A further recent study led by researchers at the University and published in 2023 has revealed how graphene “aerogel particles” could be used for adsorptive purification and the removal of contaminants from water. While a separate academic team at The University published research in 2022 showing that they were able to “pull water molecules apart” using graphene electrodes. Researchers believe that this fundamental understanding of interfacial water could be used to design better catalysts to generate hydrogen fuel from water.

“This diversity across the family of 2D materials is very helpful when applied to another key development in materials research – the stacking of various 2D materials to create a nanoscale “club sandwich” called a heterostructure. These atomically thin layers are held together by the relatively weak ‘van der Waals’ forces and, as bespoke stacks, they have opened up huge potential to create numerous ‘designer-materials’ and novel devices never possible before. Recent advances in 2D heterostructures point to a broad range of applications such as biosensors, light emitting diodes, light detectors, photovoltaic and energy storage devices, plus field effect and tunnelling transistors (for potential use in low-power integrated circuits). The revolutionary capabilities of van der Waals heterostructures have also helped push forward the development of another exciting new field in the 2D world called spintronics. This is a radically different concept in electronics in which the rotational motion ie the ‘spin’ of the electron (and its associated magnetic characteristics) can be used to carry or store information in a material in addition to its intrinsic charge. Graphene, as a 2D form of carbon, is seen as an excellent spin transporter. Applications range from greatly improved data storage, to scanners for the detection of cancer, to the development of artificial neurones and synapses for low-power neuromorphic computation.”



Self-healing materials

First reported in the early 2000s, the interest in self-healing has expanded over the last 25 years, initially propelled by the oil and gas sector, but latterly becoming an area of great interest within the space and Defence sectors.

Self-healing materials are an extraordinary set of polymers, metals, ceramics, and their composites, that are able to recover their mechanical properties after sustaining damage to their structure. Inspired by biological processes such as those seen in animals and insects, self-healing is a technology that enables a material to heal itself without intervention, although it may occur in some materials in response to external stimuli such as heat or light. Cracks and other types of damage can change the thermal, electrical and acoustic properties of a material and can lead to its eventual failure. Often, such cracks can be hard to detect during the early stages and may go unnoticed, whereas self-healing materials will initiate a repair mechanism in response to damage, both increasing the lifetime of the material and lowering costs and inefficiencies created by such degradations.

In terms of the military application of self-healing, it is more about survivability rather than functionality of systems. Materials can be developed using this technology to provide enhanced durability, anti-corrosion and extra protection properties. The commercial viability of self-healing however, remains limited because it is difficult and costly to replicate materials and scaling up their production can be challenging.

> The concept of fluids such as oils as having the ability to self-heal was inspired by the idea of a boat cutting through water; the 'cut' heals quickly because the water flows readily.

Jiaxing Huang,
McCormick School of Engineering

Self-healing coatings and fabrics is an area of great interest to the Defence industry with the potential to enhance protection, durability and performance whilst reducing maintenance costs, which could save billions. They are designed to autonomously repair damage and restore their protective properties without external intervention.
For example, by adding microcapsules such as graphene capsules or microvascular networks filled with polymers or resins to an oil based coating, when the coating is damaged, the healing agents are released and flow into the cracks and defects, effectively repairing the coating. In the case of fabrics, the materials also have the ability to repair themselves through a chemical reaction, or using shape memory and other mechanisms.

Protection: Enhanced protection for military personnel is critical to prevent exposure to extreme environments. Such examples might include when personnel are exposed to harsh chemicals or where there is potential exposure to radiation, such as when working with nuclear materials. For example, during a nuclear decommissioning procedure, protective gloves are susceptible to punctures and cuts from sharp objects, which could expose the operator to the hazardous environment. This risk could be reduced by incorporating nanomaterials and self-healing polymers into the material.
In addition to increasing the protection afforded by the material itself, its self-healing properties would enable it to reseal itself in the event of a puncture or cut. Incorporating this technology into a glove could provide the wearer with greater levels of protection when handling substances in dangerous environments.

Durability: Corrosion is a significant concern in military equipment due to exposure to harsh environments, moisture, and chemical compatibility concerns. It can also be hard to predict and detect, and can therefore go undetected, which could ultimately lead to performance and safety degradation, particularly in large metal structures such as vehicles and plane fuselages where corrosion induced degradation could lead to deterioration of the structure. Self-healing coatings can provide an extra layer of protection by sealing cracks and if the coating is damaged, the healing agents will react with the corrosive elements to form a protective barrier, inhibiting corrosion and increasing the longevity of the system. This self-healing process could reduce the need for frequent maintenance interventions and would be particularly advantageous in remote or restricted environments where resources and repair options are limited.

Biomimicry may also have a part to play in the development of self-healing materials for military use. The incorporation of mushroom enzymes and squid ring teeth into fabrics have enabled them to re-heal almost completely when cut or damaged. Enzymes are proving to be particularly effective in re-healing processes as has recently been shown in self-healing concrete. An enzyme found in red blood cells called Carbonic Anhydrase (CA) is added to the concrete powder before it is poured and when a small crack appears in the concrete, the enzyme interacts with carbon dioxide (CO_2) in the air to produce calcium carbonate crystals which mimic the concrete and promptly fill the crack. Given that concrete has a massive carbon footprint, this process of extracting CO_2 from the atmosphere could profoundly benefit the environment. This presents an opportunity for Defence to work towards its goals in decreasing its carbon footprint, while improving performance and safety.

Self-healing cars: BMW has embraced the concept of self-healing by applying a special paint finish known as 'Frozen Polaris Metallic' to the front grille of their iX model. The paint can 'self-repair' minor scratches caused by debris from the road, using heat from the car's engine.

Such advancements in technology have great potential in other industry sectors, including Defence, and scientists are most certainly taking inspiration from these.

Environmental and sustainability impact of self-healing

The concept of self-healing is a phenomenon whose relationship with the environment could be exponentially beneficial. If widely applied to environmental and resource considerations in the future, the increased recyclability, reduction in waste and the dramatically improved efficiencies in the use of resources would have a profoundly positive impact on our world.

As the use of advanced materials evolves, we are looking at a world where old becomes new and recyclable becomes re-useable - the possibilities are endless – and the faster the technology enables these processes to happen, the more likely we are to adopt them.

Gareth Appleby-Thomas
Professor of High Strain-Rate Material Response for Defence Applications/Head of the Centre for Defence Engineering at Cranfield University

Material behaviour changes when impacted by external forces (loading conditions) – with very-rapid (high strain-rate) loading leading to the establishment of hydrodynamic/shock conditions where material shear strength falls to zero enabling 'fluid-like' flow even in the solid phase.

"In military applications, material response (both effector and target) is typically governed by these behaviours, which occur on the order of millionths of a second or less.

"An understanding of shock physics is therefore a powerful tool which allows us to probe this behaviour, predicting and controlling material response to stimuli. Controlling shock/stress states can, for example, enhance the performance of ceramic armour by holding the system under compression for longer, facilitating effector defeat. It can also aid in the development of tailored and optimised body armour (mass and shape), enhance fragmentation effects from warheads, and even protect electronics packages by guiding shockwaves away from critical areas by grading of material impedance – acting to control the speed and direction of shockwave propagation."

Next generation body armour: High strain rate ceramics and smart clothing

Ceramic armours date back to 1918 and were developed for use in the military protection of individuals and vehicles because they are lightweight, possess extreme hardness only beaten by the likes of diamond and they provide high resistance to bullets and missiles.

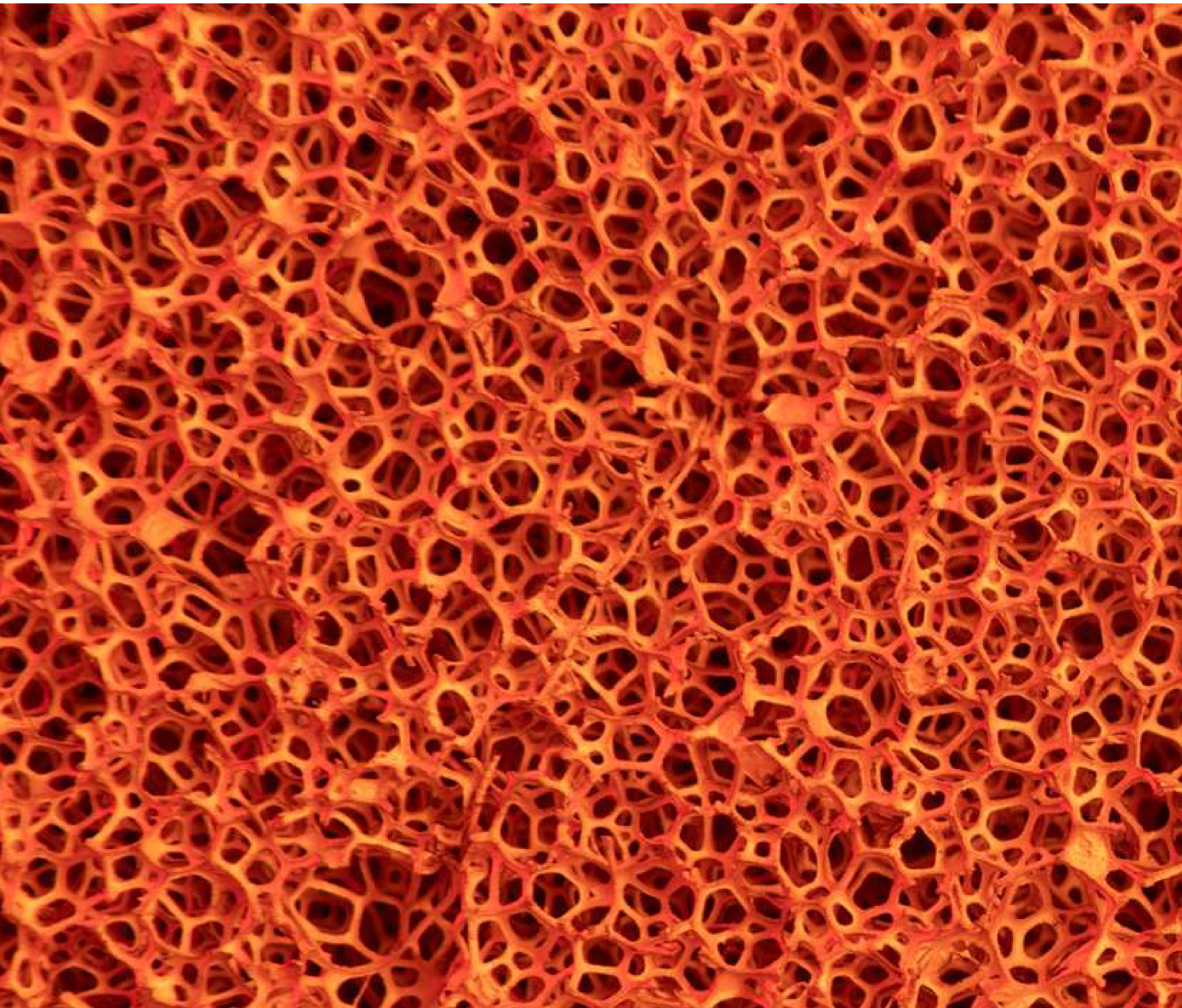
More recently, novel armour designs incorporating ceramic materials has become a very exciting area of research. The introduction of nanotechnology, such as the use of boron carbide, has led to huge improvements that result in an ultra-light, low density composite which offers extreme hardness and high impact resistance making it an ideal choice for the future of body armour.

Laboratory experiments at MIT using novel 3D printing approaches have yielded a lattice structure that can withstand more force than Kevlar or steel, while being lighter than either. This material gets its strength from specially designed nanostructures. These nanostructures have been engineered to provide optimal structural integrity with exceptional energy absorption and dissipation properties, which is crucial in providing resistance to ballistic or explosive forces. Their ability to resist heat transfer and protect against thermal blasts and high energy projectiles also provides much greater thermal protection than the traditional armour.

Metamaterials

Metamaterials, from the Greek word meta, which means 'beyond', and the Latin word 'materia', which means "matter" or "material" are another class of materials that are taking us into a futuristic world. Described as 'any type of material that is engineered to have properties that cannot be found in naturally occurring materials', metamaterials conjure up the idea of something magical. If magic is the secret power of appearing to make impossible things happen by doing special things, then perhaps this is an accurate description.

Metamaterials have special characteristics which are different from the characteristics of their individual components and which arise because of the geometry and organisation of their final structure i.e. they are governed by their structure and not by their chemistry. These unique structures, with their intelligent or innovative designs, can manipulate waves such as light or sound, by blocking, enhancing or bending the waves and the resulting effects can achieve benefits that go way beyond what is possible with conventional materials. The diversity of their potential applications has resulted in their investigation in a wide range of different fields. Within the military, this includes a vast array of applications such as power transmission, wireless charging, thermal management, energy harvesting, acoustic applications, lidars, radars, augmented reality (AR) displays and super-lenses.



Camouflage, surveillance and visibility

Concealing a moving target, whether in respect of surveillance protection in your own territory or remaining unnoticed in an enemy's territory, was originally restricted to its visible concealment, since detection techniques were based on the naked eye. However, surveillance techniques have evolved rapidly over time and the electromagnetic range of sensors now includes UV, IR, microwaves and acoustic waves. As surveillance technologies and sensors have become more sophisticated, this has driven the need for better camouflage and stealth technologies.

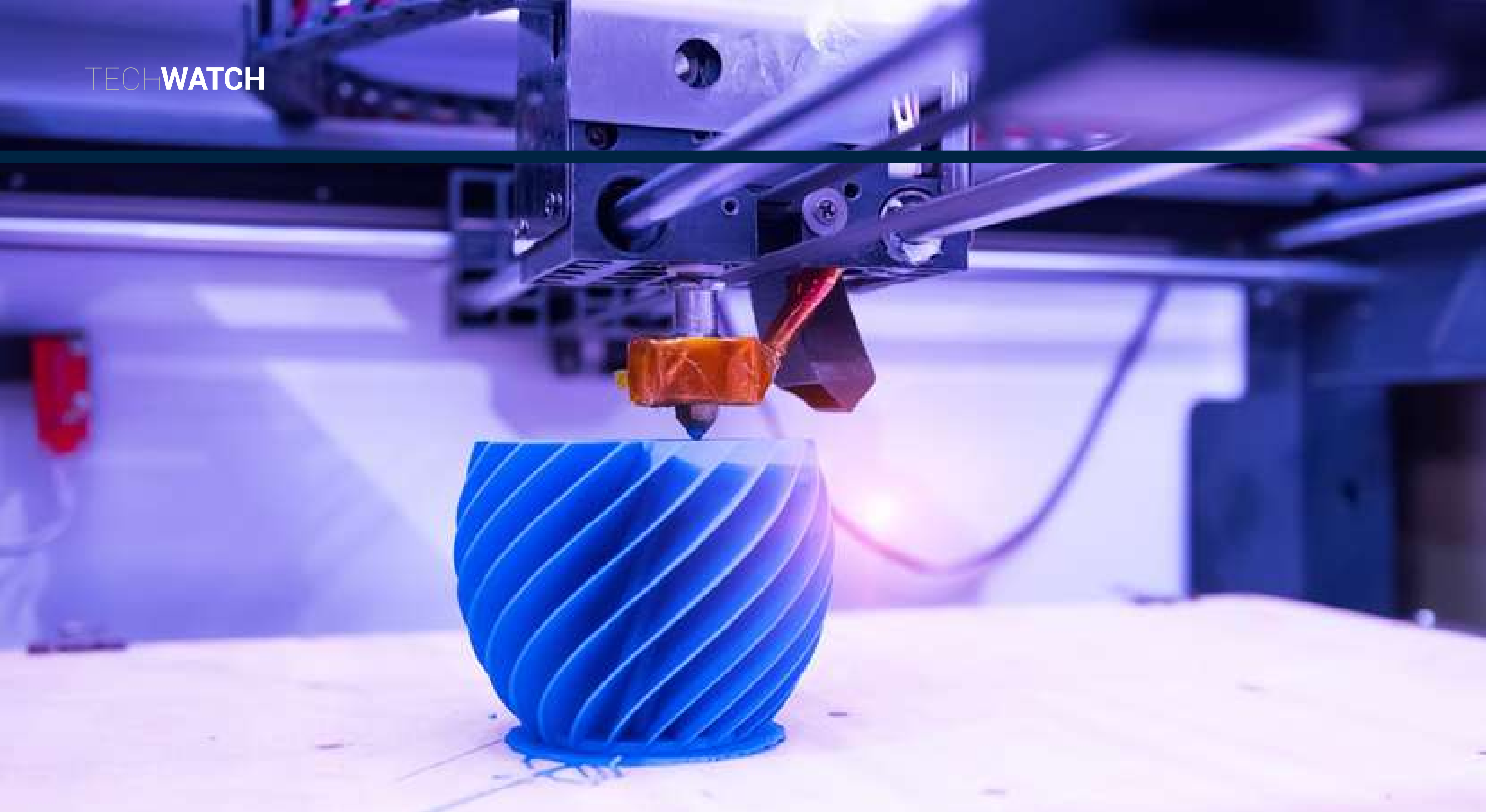
Cloaking devices: One of the most exciting studies in metamaterials is that of optical camouflage. A material can be designed to shield an object from view by controlling the light around it. A new metasurface has been developed which, when placed on an object, can bend light from the object to make it appear invisible to the eye. This 'cloaking' technology could potentially be used to improve existing technologies, such as radar-absorbing dark paint for use on stealth aircrafts and with other camouflage technologies. By controlling the reflection, absorption and transmission of the electromagnetic waves, including radar and infrared frequencies, cloaking could reduce the detectability of military vehicles, aircraft and personnel. If metamaterials could achieve a near-zero reflection, the potential for making tanks, aircraft, submarines and soldiers uniforms appear invisible to radar and sonar waves and even light could even become reality.

A thermal cloaking technique that can hide warm objects from infrared cameras is currently being developed and the technology behind it could also lead to better ways of protecting electrical circuits from heat damage.

Adaptive camouflage: Metamaterials can be engineered to exhibit adaptive properties allowing them to dynamically change their appearance such as their colour, pattern or even texture, in response to their surrounding environment. By adjusting the refractive index, polarisation or colour of the material, metamaterials can behave in a chameleon-like manner, mimicking the visual characteristics of different backgrounds or adapting to different lighting conditions (e.g. night or day) making camouflage more effective.

Imaging and targeting: The use of metamaterials in imaging and targeting systems is transforming the levels of accuracy achievable in critical aspects of military performance from situational awareness and surveillance to precision targeting. This is achieved through increased resolution, wider field of view and reduced image distortion. Flat or ultrathin and lightweight lenses which can be used in compact imaging systems and wearable devices such as head-mounted displays or augmented reality (AR) systems can provide enhanced navigation assistance and display relevant data using information overlay. The ability to design unique lenses to extend their spectral range also enables them to cover a wider portion of the electromagnetic spectrum, which includes infrared, ultraviolet and terahertz wavelengths. By capturing these additional wavelengths, military sensors can detect hidden threats and perform specialised tasks such as chemical detection.

Integration with sensor networks, where data from multiple sources such as cameras, radars and other sensors are fused together can provide a comprehensive understanding of the battlefield giving personnel a more complete picture enabling more informed tactical decisions. In the future, it is possible that a soldier's uniform could contain a fibre-embedded material to act as a computer which could collect and communicate the physiological, environmental and location data of a soldier in real-time. Uniforms with this technology could power sensors to store and analyse data whilst transmitting that data to other sources, collecting information such as body temperature and heart rate to respiratory decline or an irregular heartbeat. Future sensors may be able to detect toxin exposures and even monitor the physical effects those toxins have on a soldier, all of which could be done with very little increase in weight to their uniform.



Manufacturing metamaterials

Additive manufacturing or 3D printing offers a promising method for creating metamaterials due to its ability to create complex intricate designs with varying material properties and geometries and precise internal structures that give metamaterials their unique features. It also allows the customisation of materials which can be tailored to military specifications. Polymers, metals, ceramics and composite materials can be used in combination with specific design patterns to achieve the desired metamaterial properties.

The design of metamaterials for 3D printing involves advanced computer-aided design (CAD) software and simulation tools. These tools enable engineers to model and optimise the internal structures to achieve the desired properties. The 3D printing process involves translating the design into physical structures layer by layer. Additional treatments such as heat treatment, surface finishing or coating processes can be used to refine the metamaterials' properties or enhance their performance and they can then undergo testing such as electromagnetic or acoustic testing to verify their performance.

The adoption of 3D printing technology at the front lines of military operations can enhance operational readiness, reduce logistical dependencies and provide troops with increased flexibility and adaptability in the field. There will of course be limitations, due to factors such as power requirements, material availability and the complexity of the material being printed, but portable 'ruggedised' 3D printers have been developed specifically for military use and are capable of operating in challenging environments.

The Australian army has recently proven that it's possible to 3D print and replace armoured vehicle parts in the field during a military exercise. More than a dozen armoured personnel carrier parts were identified, 3D printed, certified and installed on the vehicles, demonstrating that metal 3D printing can produce high quality military grade parts fit for service. The US Marine Corps has also been actively exploring the use of 3D printing at the front lines with the deployment of their Mobile Fab Lab which includes 3D printers and which has been used to create items such as drone components and vehicle replacement parts.

The printing of on-demand spare parts on-site reduces the need for traditional supply chains, which can be particularly beneficial in remote or hostile environments. It can also enable the creation of customised tools and equipment tailored to specific operational needs such as weapon attachments, mounting brackets or communication device holders.

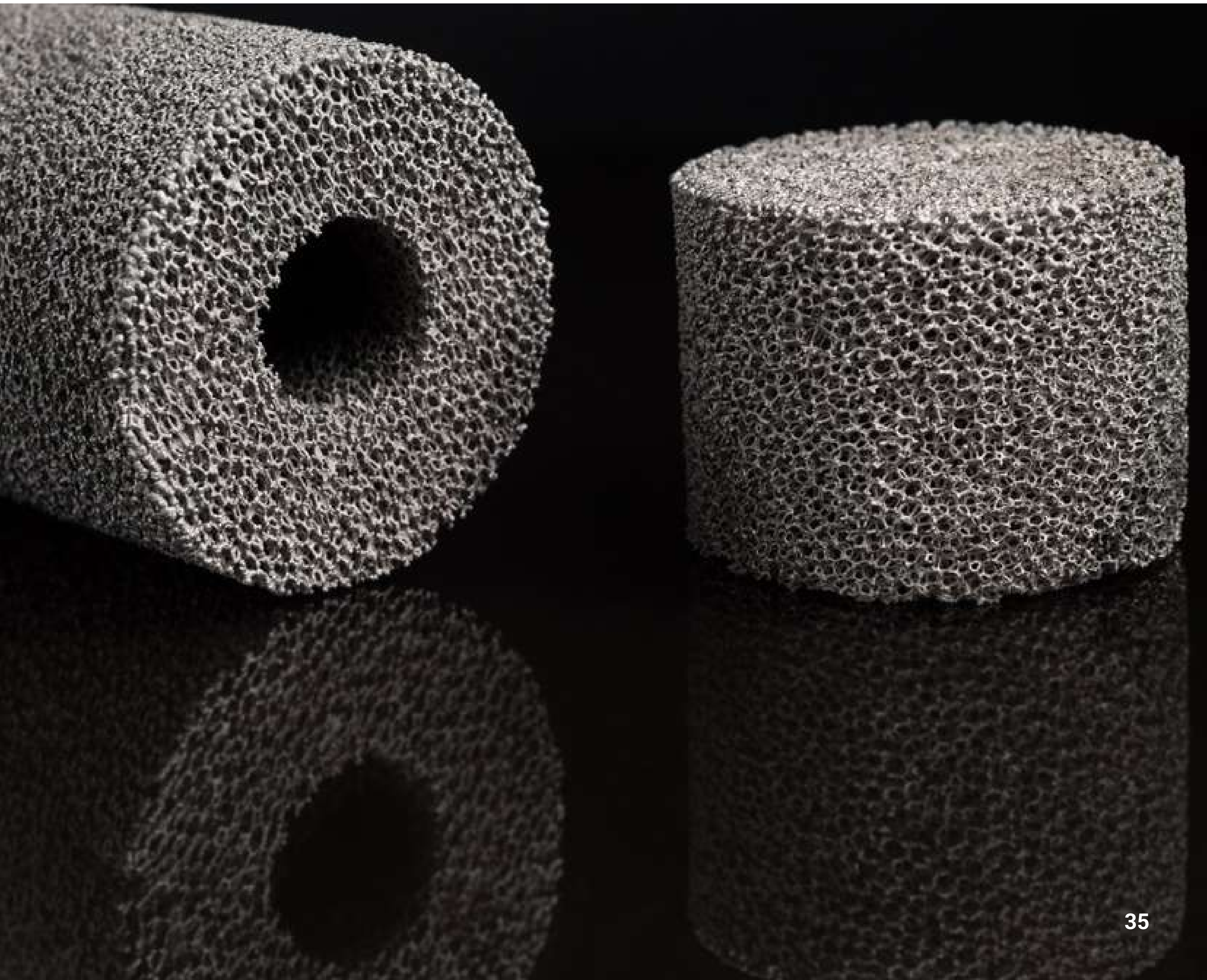
One area of 3D printing which could substantially benefit the wellbeing of troops is the production of personalised protective gear and equipment. Custom fitting helmets and body armour can be tailored to individuals' measurements, providing enhanced comfort, mobility and overall effectiveness on the battlefield.

Where will materials science take us in the next 10 years or so?

If advanced metamaterials are to live up to their expectations in reshaping our future, they must be exploited to their full potential, but there are still a number of challenges ahead.

Defence and Security organisations need novel materials to be integrated into existing platforms at pace. The nature of modern threats means that traditional innovation, experimentation and research processes are no longer aligned to the cadence of combat and the time taken to move from research to application must be shortened.

For the application of advanced materials in this sector, it is increasingly important for industry to gain a deeper understanding of operational military needs. Advanced materials need to be considered as systems rather than standalone assets to achieve their true potential. Many of the challenges that advanced materials can address require multiple materials to work together in a holistic way which requires greater collaboration between those working on the science behind advanced materials and a partnership approach with those applying that science to military equipment and personnel.



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Air Force Flies AI Copilot on U-2 Spy Plane: Exclusive Details (popularmechanics.com)

Defence Artificial Intelligence Strategy - GOV.UK (www.gov.uk)

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UK
Cody Technology Park
Ively Road, Farnborough
Hampshire, GU14 0LX
United Kingdom

+44 (0)1252 392000

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