Science and Technology Organization

Science & Technology Trends 2023-2043

Across the Physical, Biological, and Information Domains

NATO Science & Technology Organization

VOLUME 2: Analysis

⚠ DISCLAIMER

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Foreword

As the world's largest collaborative forum for science and technology (S&T) research in security and defence, the STO aims to empower NATO's technological edge. It works to achieve this vision through an active network of around 5,000 dedicated scientists, engineers, and analysts who carry out more than 300 research activities annually. Researching S&T trends, developing new forecasting methodologies, and identifying novel and disruptive S&T are all critical aspects of this work. As a community of S&T experts, the STO collaborative network provides unparalleled insights into the latest trends in defence and security technology, as well as their future evolution and impact. This second volume of Science & Technology Trends 2023-2043 highlights this network's methods, data, and insights on emerging and disruptive technologies, providing a deep dive into the foundations upon which Volume 1 of this report is built.

Mr. John-Mikal Størdal
Director, NATO STO Collaboration Support Office

Forecasting the development of S&T potentially relevant to NATO over a twenty-year period is daunting. However, through rigorous and wide-ranging qualitative and quantitative methods, insights into the state, rate, and impact of S&T relevant for defence and security can be constructed. Combining insights from futures studies, STO technology watch, serious gaming, research meta-analysis, surveying expert opinion, and reviewing national research programmes provides useful insights into S&T developments. This volume summarises and synthesises these activities, providing a snapshot of future EDT development. It reflects the efforts of many individuals and 70 years of history and intellectual richness of the STO as NATO's *original innovation engine*.

Dr. Catherine Warner
Director, NATO STO Centre for Maritime Research and Experimentation

Foreword cont.

Properly assessing the state, rate, and impact on the Alliance of EDTs and other promising technologies requires an evidence-based understanding of the overarching scientific and technological ecosystem, including weak technology signals. Various data sources and techniques were employed to support the analysis undertaken in this report. Over four thousand articles, books, meta-studies, documents, and reports were collected, collated, reviewed, and assessed. Supplementing this collection, the NATO Office of the Chief Scientist and the NATO Communications and Information Agency (NCIA) developed the Science & Technology Ecosystem Analysis Model (STEAM). STEAM draws upon a growing collection of millions of English-language journal articles, pre-prints, and abstracts. STEAM allows deeper insights into EDTs and creatively exploits Artificial Intelligence to better understand developments within the S&T ecosystem, ultimately putting the analysis on a stronger footing. Nevertheless, STEAM is still a work in progress, with its analysis more indicative than definitive. With an eye towards the next S&T trends assessment, plans are being made to expand STEAM to include patent data, non-English language articles, and deeper AI-enabled analysis of S&T trends. In addition, the planned role of STEAM will be enlarged into a broader business intelligence tool. This will enable a deeper understanding of international research and capability development collaboration patterns while supporting NATO's S&T portfolio management. In turn, this will allow NATO to anticipate, deliver and react to EDT developments and enabled capabilities.

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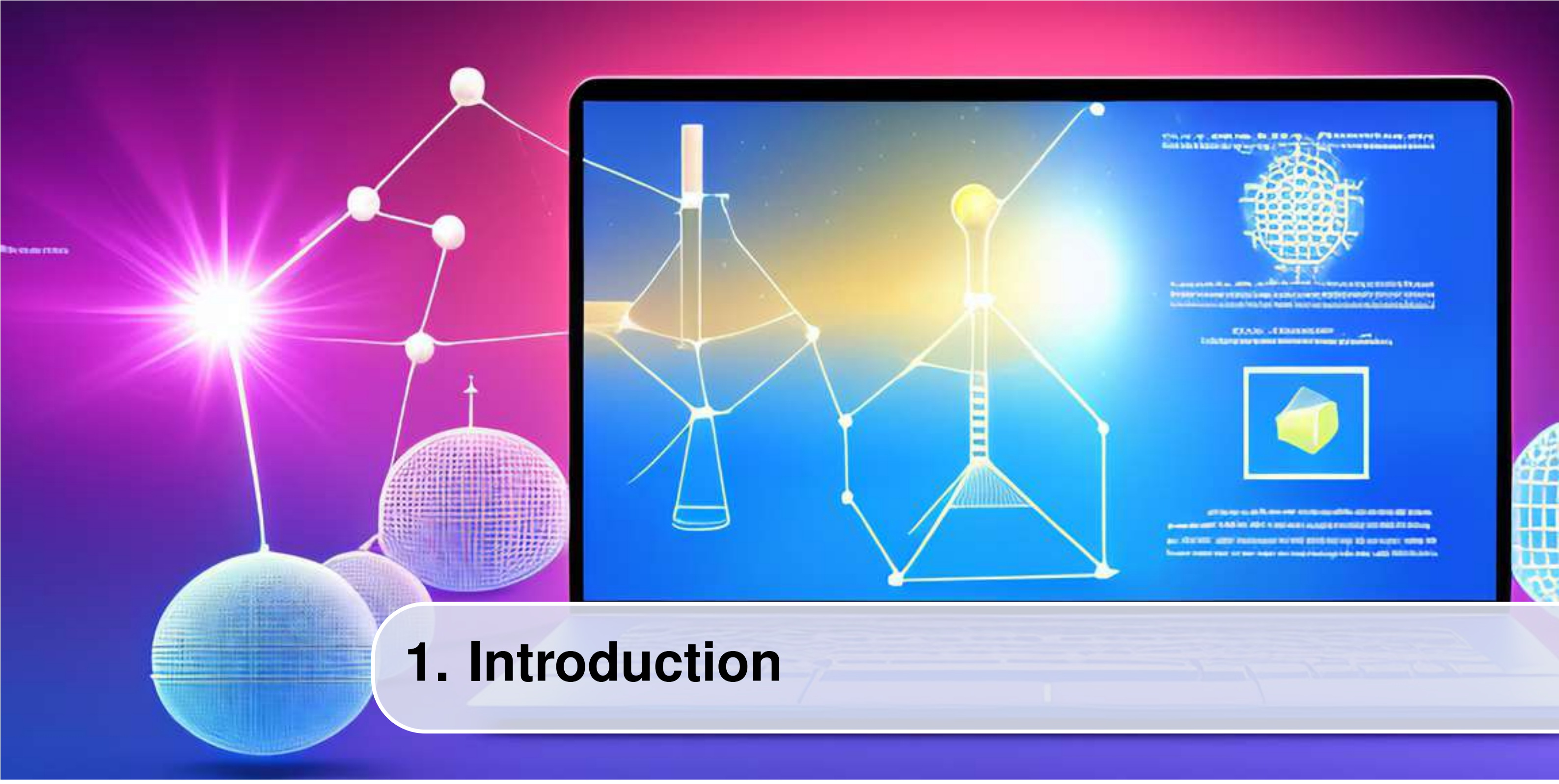
Executive Summary - Volume 2

Science & Technology Trends: 2023-2043 provides an updated assessment of Science & Technology (S&T) trends and their potential impact on NATO military operations, defence capabilities, enterprise functions, and political decision space. Such an assessment draws upon the collective insights and research activities of the NATO Science & Technology Organization (STO), its collaborative network of over five thousand active scientists, analysts, researchers, engineers, and associated research facilities. These insights have been combined with an extensive review of the open-source S&T literature, selected national research programs, NATO STO technology watch activities, (serious) research games, STO CPoW (Collaborative Programme of Work) activities, and NATO innovation endeavours.

Given the volume of work undertaken, the report has been split into two volumes. The first summarises the analysis and discusses, in general terms, key geopolitical and social trends impacted by S&T developments or the impact of those developments themselves. The second provides a detailed discussion of the methodology, data, and analysis that underpins the recommendations and observations in Volume 1. This second volume also provides a *deep dive* into the individual emerging and disruptive technologies, their potential impact on military capabilities, and their impact on other EDTs. Extensive use is made of quantitative analyses of recent academic articles, scientometric assessments, and a survey of the STO network to assess the state, rate, and potential impact of these technologies. Extensive references are also provided to support the conclusions and facilitate an even deeper analysis by the reader.



1. Introduction

The Future - Mapping Out the Probability Space

"We are still the masters of our fate. Rational thinking, even assisted by any conceivable electronic computors, cannot predict the future. All it can do is to map out the probability space as it appears at the present and which will be different tomorrow when one of the infinity of possible states will have materialised. Technological and social inventions are broadening this probability space all the time; it is now incomparably larger than it was before the industrial revolution—for good or for evil." — *Dennis Gabor* [1]

1.1 Context

Since the last Science and Technology (S&T) trends assessment [2], the world has seen technological, social and geopolitical change and disruption at an unprecedented level. Over the last three years, NATO, and the world as a whole, have been challenged by the pandemic of the century (COVID-19), the Russian-Ukrainian war, the withdrawal of NATO forces from Afghanistan, significant climate disruption, the rise of potential nuclear powers, inflation, increased tensions in the Asia-Pacific, the challenge of techno-authoritarianism, as well as insatiable S&T progress, especially in the areas of *Data*, *Quantum*, *Biotechnology*, *Autonomy* and *AI*.

NATO is a unique consultative and collaborative military and political framework. This collaboration extends beyond the military, and political realms to science and technology, enabling the application of state-of-the-art validated knowledge for defence and security purposes. NATO S&T activities embrace scientific research, technology development, analytical assessments, capability planning, experimentation, and a wide range of related scientific activities [3].

The Science and Technology Organization (STO) plays a decisive role in supporting *innovation*; providing profound *insights* into alliance challenges; ensuring the *integration* of Alliance capabilities; and making available an *interconnected* network of science and knowledge workers capable of providing evidence-based *advice* to NATO, as well as alliance members and partners. At its core, the role of NATO's S&T community is to [3]:

> *"... maintain NATO's scientific and technological advantage by generating, sharing and utilising advanced scientific knowledge, technological developments and innovation to support the alliance's core tasks."*

To support the strategic development of such technologies, the STO is responsible for assessing S&T futures for senior leadership. As noted in the STO charter (2012) [3]:

> *"To fulfil its mission, the STO will ... provide advice to NATO and Nations' leadership on significant S&T issues, including the identification of emerging technologies, and the assessment of their impact on defence and security."*

1.2 Analysis

Science & Technology Trends (2023-2043) provides context and a foundation for a NATO technology strategy, Alliance capability development and the NATO S&T programmes of work. The core objective is to increase the understanding within the Alliance of the potential for S&T developments to enhance or threaten Alliance military operations. Increased awareness of the state, the projected rate of development, and the anticipated impact of such technologies should lead to enhanced future capabilities, better strategic decision-making and improved S&T portfolio management. Such an assessment does not attempt to predict the future in detail (a difficult task at best and impossible at worst). Instead, it seeks to provide a context for anticipating the possible development of S&T and its potential impact on the Alliance.

Analyses of technology trends and the associated process of technology watch are critical steps to identify new militarily important technologies and communicate the potential impact of these technologies on NATO and national leadership. Those recognised technologies hold the promise to enable the development of disruptive military capabilities for Alliance (BLUE) and potential adversarial (RED) forces. The report assesses S&T trends (emerging and disruptive technologies) projected to impact NATO operations, capability development and core functions over the next 20 years and explores the implications of these changes. These S&T areas are broad, have significant overlaps, are not orthogonal and are expected to:

- Mature over 20 years;
- Be transformative or revolutionary; and,
- Be emergent or create generational shifts in S&T development.

1.3 Approach

This report aims to reach a wide audience both inside and outside of NATO and its partners. We do so to stimulate a frank and open discussion of potential opportunities and risks presented by technological developments over the next 20 years. As such, the report is based strictly on the following:

- Technology trends discussed in the open literature;
- A global perspective on technological progress;
- Scientometric analysis; and,
- Logical reasoning informed by Alliance S&T expertise and technology watch activities.

Defence Ministers approved a canonical set of EDTs and an associated roadmap in October 2019. In 2022, the 2022 Alliance Heads of State and Government Madrid summit authorised two more priority technologies for consideration, *Novel Materials and Agile Manufacturing* and *Energy and Propulsion*. In keeping with the STO's mandate to continue to monitor and evaluate the broader technological landscape, this report also considers the status of recent developments in *Electronics & Electromagnetic (E & EM)* technologies, including developments in directed energy weapons. As such, 10 EDTs are considered in detail in this report, each broken down into technology focus areas, highlighting specific areas of research and development (R&D). Chapter 2 discusses this decomposition in further detail.

Science & Technology Trends: 2023-2043 supersedes the *Science & Technology Trends: 2020-2040* report [2] but draws heavily upon its foundations, structure, insights and lessons learned. Indeed, this report is best considered an update to the previous report. As before, the report exploits a broad range of open-source reports, internal assessments, NATO EDT and innovation activities, technology reviews, serious games, quantitative analysis and futures studies to develop a comprehensive understanding of the future technology landscape. These sources include:

- Existing NATO S&T trend and future security environment studies, strategies, discussions and assessments;
- Technology watch activities conducted by the STO, including existing Technology Watch Cards (TWC) (current as of October 2022), Chief Scientist Reports, (serious) technology games and Von Kármán Horizon Scans (vKHS);
- Meta-analyses and reviews of open source technology watch and futures research from defence, security and industry sources;
- Internal and external quantitative analysis of academic publications, patents and research activities;
- Scientometric analysis of the global S&T ecosystem;
- Surveys of the STO network and panels seeking insights into technological developments, readiness and maturity;
- NATO-sponsored EDT workshops and innovation system engagements; and,
- Alliance and partner EDT studies and research programs.

1.4 Overview

Within the following appendices, an analysis is presented of identified and militarily relevant S&T trends, which may impact NATO capability development and operational challenges over the upcoming 20 years (2023-2043). The approach and key data sources used to conduct this assessment are described in Chapter 2. Separate appendices provide a more detailed exploration of each EDT, drawing heavily upon STO research and technology watch activities. This section also includes *Conjecture Cards*, short vignettes that describe the potential future application of these technologies. They are included to help contextualise the potential impact of these technologies *but do not necessarily represent research interests or activities being undertaken by NATO or members of the Alliance*.

The bibliography at the end of this document provides an extensive list of useful references. These are also used throughout the body of the text where appropriate. When using the Adobe PDF version of the report, *clicking* on a numbered reference will take the reader to the relevant entry in the bibliography. If desired and available, *clicking* on the provided URL (i.e., web-link) will allow the reader to open the source reference directly for further study and exploration of the topic.

2. Methodology

Forecasting:
"Finding patterns is easy in any kind of data-rich environment; that's what mediocre gamblers do. The key is in determining whether the patterns represent noise or signal." - *Nate Silver* [4]

2.1 Description

Forecasting S&T development is a challenging task that demands a structured, thoughtful and information-intensive process. We have taken such an approach in developing this report, drawing from multiple sources and assessments while seeking common patterns or indicators from within the information available. For transparency and challenge, the approach and key data sources used to conduct this assessment are described in the following sections.

2.2 Assessment

To understand the state, rate and impact of EDT development, it is necessary to consider the following:

- technological maturity (current and future);
- keywords defining sub-areas and other technological connections;
- level of *attention* or *hype* around a particular technology or scientific area;
- integration into NATO operational and enterprise capabilities; and,
- potential military impact.

Such an assessment is problematic as each EDT encompasses many different core aspects, each potentially at a different stage of development. As a result, for this report, each EDT is broken into a second level of areas identified for focused development or research. We refer to these as EDT *technology focus areas*. These areas are very broad, and assessments of the state and rate of development will necessarily be somewhat *fuzzy* in nature. The report employs several approaches described in more detail below.

2.2.1 Technological Maturity

In general successful S&T proceeds along a developmental path captured as *technology readiness levels (TRLs)*, originally developed by NASA [5, 6]. Each level is a potential *off-ramp* or *pause* for that particular technology (see Table 2.1). These levels provide a useful *shorthand* for interpreting technology maturity and, as such, are widely used within industry and government. Similar frameworks [7, 8, 9] are available for human, algorithm, manufacturing, commercialisation, machine learning, and technology commitment readiness levels.

Table 2.1: *Technology Readiness Levels.*

TRL 9	Actual system proven through successful mission operations.
TRL 8	Actual system completed and qualified through test and demonstration.
TRL 7	System prototype demonstration in a space environment.
TRL 6	System/subsystem model or prototype demonstration in a relevant environment.
TRL 5	Component and/or breadboard validation in a relevant environment.
TRL 4	Component and/or breadboard validation in a laboratory environment.
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept.
TRL 2	Technology concept and/or application formulated.
TRL 1	Basic principles observed and reported.

Technologies, or the underlying sciences, may be unsuccessful in generating new operational capabilities or pause at any point along the path to TRL 9+ due to several factors, including lagging dependencies on other technologies, costs, ethics, policies or fundamental physical, information or human limits. Evaluating when these technologies will reach TRL 9 assesses full technological maturity and utility for operational and enterprise capabilities.

Unsuccessful developments are necessary within S&T to inform and ultimately give rise to new approaches and technologies that may be more successful in moving from basic principles to operational capabilities. As the American inventor Thomas Edison stated: *"I have gotten a lot of results! I know several thousand things that won't work."* [10]. Thus, constructive failure is a feature of scientific and technological developments, not a *bug*.

We assess the current TRL levels primarily through STO Technology watch activities assessments, a survey of the STO experts network, related futures assessments, and references to several available TRL calculators [11]. It should be noted that emerging technologies are usually in the range of TRL 1 through 5 [12].

2.2.2 Keywords

Keywords associated with an EDT provide insights into research areas, sub-areas and synergies. Keywords for this report are drawn from several quantitative and qualitative sources. They include analysis of publication databases, publication guidelines (e.g. IEEE [13]), critical technology lists [14, 15, 16] and STO survey results.

2.2.3 Attention

Technological development is distinctly cyclic on many levels. The most well-known of these cycles is the *Gartner Hype Cycle* [17] (Figure 2.1), itself based on Howard Fosdick's work on the sociology of technology adoption [18, 19]. While this relates to TRLs, such an assessment reflects a socio-technical perspective on the state of development of technology and the likelihood of continued advancements in this area. Essentially this captures *buzz*, or more accurately *attention* around a technology.

Technologies do not always progress from the beginning to the end of such a cycle; indeed, as noted earlier, most technologies *fail*. Moreover, many avenues of science or technological discovery never break through to ignite innovation. Instead, they disappear from public consciousness after initial enthusiasm as unproductive avenues of development, or they may appear later on as new convergent developments reinvigorating an old idea. Finally, even successful technologies may reappear as novel ideas create innovation triggers and old technologies become so integrated into production systems that the original connection is lost on all but the most technically minded. Such an evolutionary process built on *heroic failures* [20] or *creative errors* is essential to scientific and technological progress, as lessons and ideas that arise will often lead to entirely new areas for exploration, innovation and development.

During a hype cycle, a successful trending technology will (arguably) ultimately go through five key phases: [21, 22]:

- **Innovation Trigger**: After considerable supporting research, a potential new technology breakthrough shows promise. This initial innovation trigger builds upon early experimentation and results in proof-of-concept stories, and media interest is triggered. This spark yields growing publicity and internet search activity. However, no viable product exists at this stage, and commercial viability remains unproven.

- **Peak of Inflated Expectations**: Early publicity produces many success stories — often accompanied by scores of failures. Interest (e.g. as measured by web searches) is at an all-time peak. Some innovative companies take action; many do not.

- **Trough of Disillusionment**: The limitations of the technology become clear, and some implementation efforts fail to produce useful results. As a result, general interest falls, and negative stories become more frequent, although these may be overly pessimistic. Eventually, some developers and producers move on to other areas or fail outright. A bifurcation occurs at this point, where investment and continued developments only occur if continued progress can be shown through the refinement of the underlying technology, the development of a better understanding of where this technology is most applicable or a convergence of other technologies or demand. If this does not happen, the technology will eventually be deemed *unproductive* and disappear entirely from consideration, or return to the *start gate* to await further developments, technological convergence or changing circumstances.

- **Slope of Enlightenment**: With a better understanding of what is practical and where it can be best applied, the potential begins to crystallise and become more widely understood and appreciated. Next-generation products occur, and positive attention increases with more successful trials and pilot products. Some companies remain cautious.

- **Plateau of Productivity**: Mainstream adoption occurs. With a better understanding of value, applicability and limitations, the technology has found its market. Issues and new ideas may still arise, potentially kicking off a new cycle. Otherwise, the technology becomes so well integrated into the technological landscape that its use becomes commonplace until a new technological advance supplants it.

Balancing out the highs of *inflated expectations* and the lows of the *trough of disillusionment* is critical in making investment and long-term capability decisions. The exact placement of technology on such a curve is problematic, as is the focus on hype rather than a measurable quantity, such as attention. This report will distinguish between emerging technologies (those in the early steps of the curve) and disruptive technologies (typically towards the middle to end of the Gartner curve).

In contrast to the last S&T report [2] this report does not track hype trends, although the Gartner annual report [23] was consulted, along with many other sources. This decision was based on a belief that the hype assessment added little to the discussion for NATO above and beyond the TRL assessment. Figure 2.1 presents the Gartner consolidated assessment for all emerging technologies considered to be of interest to a general business audience as assessed in 2022. While this is very useful as a source of data and analysis for understanding EDTs, it does not focus on defence applications and considers developments over a 2 to 10-year horizon.

One of the more interesting observations in the 2022 emerging technologies list is the identification of three major themes: evolving/expanding immersive experiences, accelerated AI automation, and

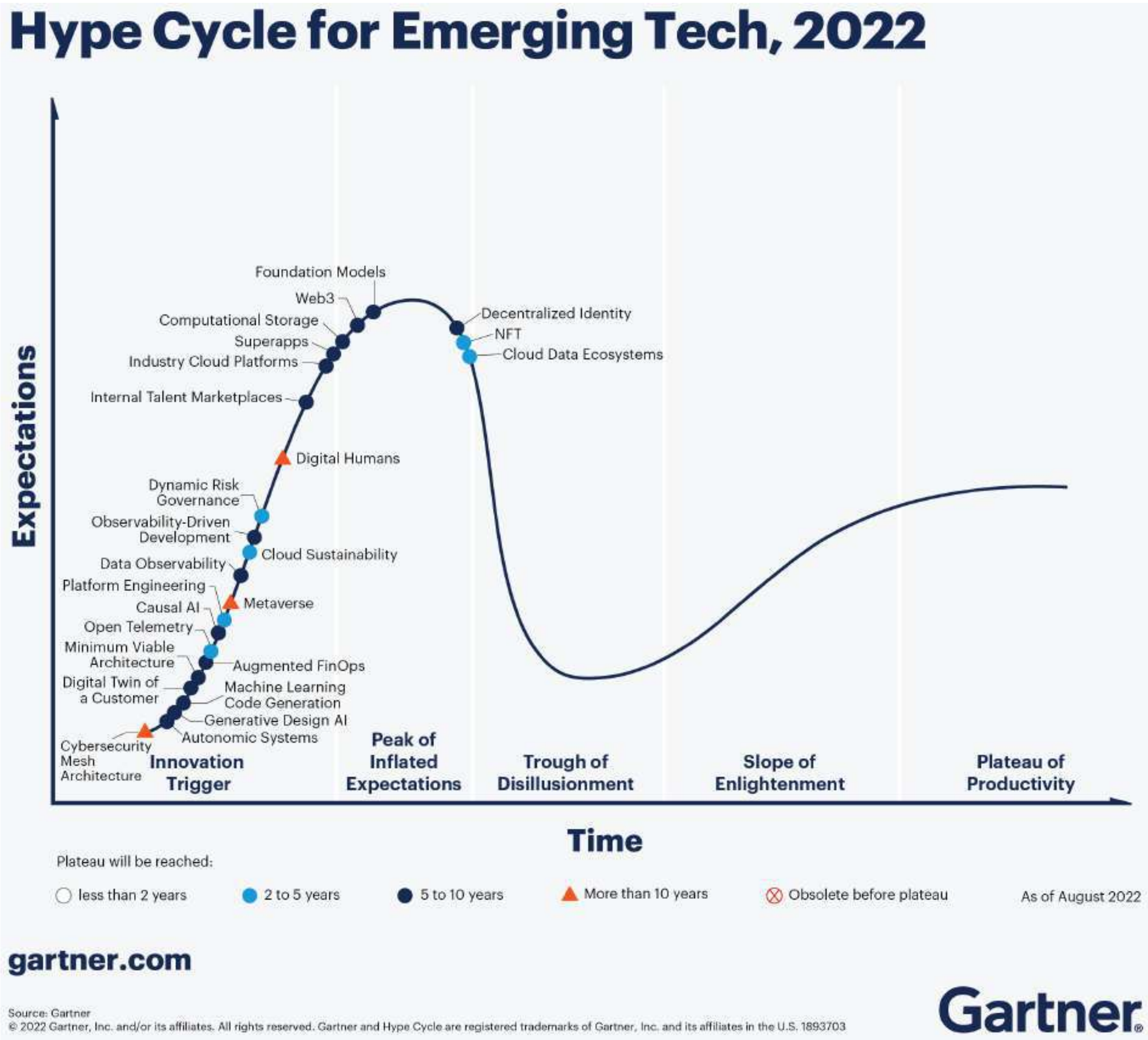


Figure 2.1: *Gartner Hype Cycle 2022 (CREDIT: Gartner [24]).*

optimised technologist delivery. When explored in detail, these themes align well with this report's identified technology themes (intelligent, interconnected, decentralised, and digital), which were carried over from [2].

Figure 2.2 presents the Gartner assessment for sub-areas associated with AI, considered to be of interest to a general business audience as assessed in 2022.

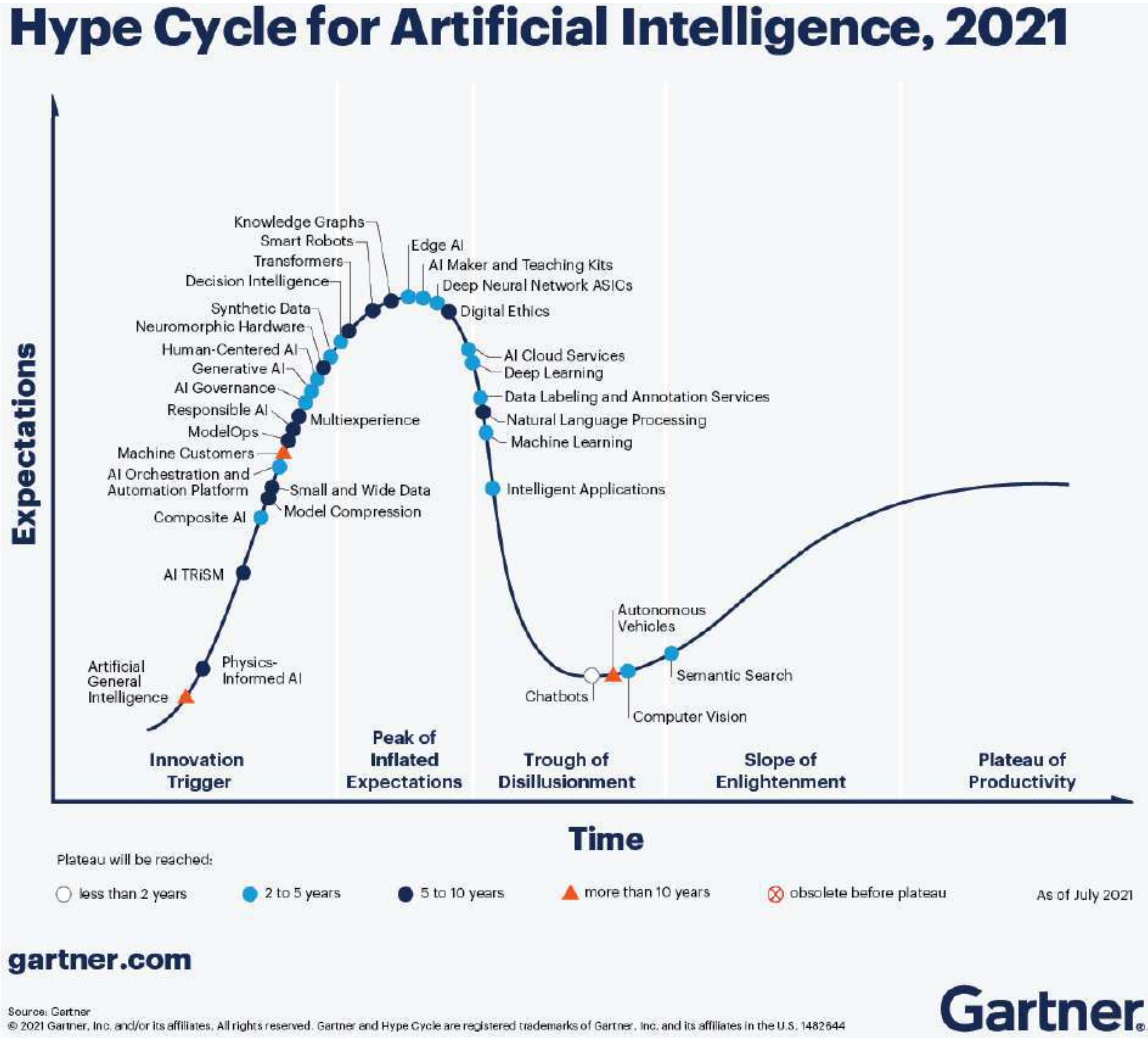


Figure 2.2: Gartner Hype Cycle - Artificial Intelligence 2021 (CREDIT: Gartner [25]).

2.2.4 Capability

For NATO, EDTs are primarily of interest through their influence on current and future Alliance defence capabilities. To better connect EDTs to their military impact, each EDT is evaluated for its potential effect on NATO operational capabilities. NATO's operational capability taxonomy [26] provides a structured list of capabilities and sub-capabilities. In addition, the first level capability *Enable* is added to this list to capture NATO enterprise functions unrelated to a specific military operation. The first level capabilities used are:

- **ENABLE**: This capability supports the strategic or organisational functions necessary to enable Alliance political and military operations in all domains, levels, and across all MCAs. For our purposes, *Enable* includes additional basic business processes such as *Govern*, *Generate*, and *Operate*, identified in [26]. These capabilities are required to run and manage any large defence and security establishment. Such generic processes focus on support services required throughout the defence enterprise, such as financial, human resources, policy development, defence planning, legal, etc., interfacing with almost every other process in the enterprise, whether governance, strategy, force development, or operations.

- **PREPARE**: To establish, prepare and sustain sufficient and effective presence at the right time, including building up forces through appropriate and graduated readiness, to meet any requirements, keeping enough flexibility to adapt to possible changes in the strategic environment. These also include the capabilities to contribute to Deterrence and Defence, Resilience and Projecting Stability.
- **PROJECT**: To conduct strategic deployment of headquarters (both for the NATO Force Structure and at a national level), forces and capabilities supporting any Alliance mission. These also include the capability to contribute to deterrence.
- **SUSTAIN**: To plan and execute the timely support and sustainment of forces, including essential military infrastructure, movement and transportation, military engineering support, contracting, supply, maintenance, services management, basing support and health and medical support.
- **ENGAGE**: To perform the tasks that contribute directly to achieving mission goals within collective defence, crisis management, and cooperative security operations. It includes all capabilities required to defeat, if necessary, adversaries as well as other capabilities such as, among other things, those needed to evacuate non-combatants, prevent the use of force by opponents, train local security forces and participate in stabilisation and reconstruction.
- **PROTECT**: To conduct strategic deployment of headquarters (both for the NATO Force Structure and at a national level), forces and capabilities supporting any Alliance mission. These also include the capability to contribute to deterrence.
- **INFORM**: To establish and maintain the situational awareness and knowledge required to allow commanders at all levels to make timely and informed decisions.
- **CONSULT, COMMAND, AND CONTROL (C3)**: For commanders to exercise authority over and direct the full spectrum of assigned and attached forces in accomplishing the mission. Include the capability: to communicate and coordinate with other actors which are present or involved in the operational area and effective information exchange with the political and military leadership; the capability to plan, employ and coordinate civilian activities with other actors and organisations; capability for nuclear planning and political consultation that allow the rapid development of nuclear employment options in crisis and war, should circumstances so dictate.

An assessment is presented for *Enable* and the first level of the operational taxonomy only: *Prepare*, *Project*, *Engage*, *C3*, *Sustain*, *Protect*, and *Inform*. This assessment is presented later in Appendices A - J.

2.2.5 Impact

Assessing the potential impact of emerging or disruptive technologies is a complex process. To do so successfully requires consideration of the threat environment (current and future), legal & policy constraints, political factors, and investment decisions, as well as estimating the potential for organisational uptake (e.g. entrepreneurial drive and risk tolerance) [27]. These estimates are further compounded if the road to disruption involves complex combinations of such technologies (e.g. synergies) or requires the development of new concepts.

For purposes of this report we follow [27], defining *Impact* in a somewhat subjective and imprecise manner as (Table 2.2):

Table 2.2: EDT Impact.

Scale	Performance: speed, range, accuracy, lethality, survivability, affordability, availability, dependability or other defining capability characteristic
Moderate	10 - 50 improvement %
High	50 - 100 improvement %
Revolutionary	Greater than 100%, or conducting activities or tasks hitherto deemed impractical or impossible

Assessments in this report of the military impact of relevant technologies are based predominately on the results captured in [2] and a *wisdom-of-the-crowd"* assessment, supported by a survey of the NATO STO network. An in-depth discussion of the survey results may be found in Appendix K.

2.3 Information Sources

2.3.1 NATO Reports and Studies

The following NATO-released documents were used in the preparation of this report:

Framework for Future Alliance Operations (2018)

In future operations, NATO must continually evolve, adapt, and innovate to maintain a decision and capability advantage (credible, networked, aware, agile and resilient). *The Framework for Future Alliance Operations 2018* (FFAO) [28] provides a futures perspective supporting such developments. It informs the Alliance of opportunities to improve its defence and deterrence posture and its ability to project stability, ensuring it remains continuously proactive, ready and responsive. It describes how NATO forces can keep the edge and retain the ability to defeat potential adversaries on future battlefields. Finally, it provides military advice identifying force characteristics and abilities the Alliance needs to retain the military edge, address upcoming challenges, and seize future opportunities.

The FFAO identifies several *instability situations*, potential events of critical significance, which could reach the threshold requiring the Alliance to use military forces. These instability situations provide a useful framework for assessing the impact of EDTs, both from a threat and opportunities perspective, and are listed below:

Weapons of Mass Destruction	*Conventional War*	*Threat Escalation*
Hybrid War	*Irregular War*	*Terrorism*
Global Commons Disruption	*Critical Infrastructure Attack*	*Information Warfare*
Cyberattack	*Governance Challenges*	*Endangerment of Civilian Populations*
Mass Migration	*Pandemic Disease*	*Natural or Man-made Disaster*

The report identifies anticipated future operational challenges. These include the impact of technological advances; new concepts of operation (e.g. global strike, hybrid, and cyberspace operations); and shifts in the geopolitical landscape. Of interest to the assessment of EDTs, the report notes that future-armed conflict is expected to be characterised by any combination of:

- Adversaries (state and non-state) global in scope and employing indirect approaches;
- A greater role of super-empowered individuals and non-state actors that produce hard-to-predict effects;
- A compression of strategic, operational and tactical decision-making, blurring decision-making processes;
- More inter-connectivity across the land, sea, air, cyber, and space domains;
- Small units fighting over greater distances;
- Operations in the cyberspace domain, global commons, urban areas, and subterranean areas;
- Rapidly emerging and widely available technologies;

- The use of human enhancement and the rising importance of the human-machine interface;
- The use of automated and potentially autonomous systems and operations in which humans are not directly involved in the decision cycle;
- New classes of weapons that can cause widespread destruction;
- Greater number of sensors and the proliferation of the internet of things;
- An expanded access to knowledge, including the ability to conduct large-scale advanced data analytics to gain a military advantage; and,
- Weaponised information activities intended to influence populations alone or in support of armed conflict.

Emerging or Disruptive Technologies Roadmap (2019)

NATO Defence Ministers approved an EDT Roadmap in October 2019. This provided a canonical list of seven EDTs providing structure to subsequent innovation, strategies and associated roadmap developments within NATO over the last three years (e.g. [29, 30]. Following this, in February 2021, NATO Defence Ministers approved an EDT strategy to guide NATO's development of EDT policy [31].

Science & Technology Trends: 2020-2040 (2020)

This report [2], published in March of 2020, highlighted S&T trends assessed by the NATO STO. It was the second comprehensive report on emerging trends in S&T by the NATO STO, with the first being published in 2017 [32]. The report exploited a broad range of open-source reports, internal assessments, and studies of potential futures to develop a comprehensive understanding of the future technology landscape. These sources included: 1) Existing NATO S&T trend and future security environment studies, discussions and assessments; 2) Technology watch activities conducted by the S&T Organisation, including existing Technology Watch Cards (TWC) (current as of Feb 2019) and von Kármán Horizon Scans (vKHS); 3) Meta-analyses and reviews of open-source technology watch and futures research articles/reports from defence, security, and industry sources; 4) NATO-sponsored EDT workshops and innovation system engagements; and, 5) Alliance and partner EDT studies and research programs.

The EDT taxonomy used in the 2020 S&T Trends report [2] builds on the canonical set of seven EDTs, adding Materials (Novel Materials and Agile Manufacturing) based on STO foresight activities. Defence Ministers approved the first seven EDTs in October 2019, while the STO added an eighth (Materials) area for future consideration and development. Including an eighth EDT recognises that materials and manufacturing research are well-developed technologically yet increasingly disruptive (e.g. 3D/4D manufacturing). At the same time, some aspects are emergent (e.g. novel materials, bio-manufacturing, and nanotechnologies).

These eight highly interrelated S&T areas are still forecasted to be major strategic disruptors over the next 20 years. These S&T areas are either currently in nascent development stages or undergoing rapid revolutionary development. The EDTs identified were:

Data	*Artificial Intelligence (AI)*	*Autonomy*	*Space*	*Hypersonics*
Quantum	*Biotechnology*	*Materials*		

2.3.2 NATO STO Technology Watch Activities

Collaborative Research Program (CPoW) NATO S&T Priority Areas

A set of NATO research priorities guides S&T conducted under the auspices of the STO, as agreed to by the Nations through the S&T Board (STB). These priorities influence medium to long-term S&T planning across NATO and inform S&T investment decisions within the Nations. In addition, the STO maintains an understanding of current and future S&T, including broad themes and EDTs, through engagement with the approximately 5000 active scientists, engineers and analysts participating in the collaborative research program (CPoW).

The STO S&T priorities are organised into ten S&T Areas, spanning the Human, information and physical sciences. Each area has a specific defined *Targets of Emphasis (TOE)*. While there are many ways of organising S&T activities, the ten S&T Areas provide a broad and useful reference frame for research activities, while the TOEs provide selective focus and orientation. The priorities are constructed independent of physical domains, scientific disciplines, or specific applications, while the language is situated between the words used to express requirements and S&T solutions. The employment of the priorities focuses on S&T efforts that support innovative capabilities for the Alliance's forces, inform future military specifications, and provide strategic advice to senior decision-makers. Table 2.3 summarises these priorities and associated targets of emphasis.

Table 2.3: *NATO S&T Priorities.*

Domain	NATO S&T Priority Areas	Targets of Emphasis
HUMAN	Advanced Human Performance & Health	Medical Solutions for Health Optimisation
		Human Resiliency
		Enhanced Cognitive Performance
		Human & Machine Interfaces
	Cultural, Social & Organisational Behaviours	Social Influence
		Political Influence
		Cultural Communications
		Group & Organisational Behaviour
INFORMATION	Data Collection and Processing	EM Sensors
		Non-EM Sensors
		Sensor Integration & Networks
		Advanced Signal Processing
	Information Analysis & Decision Support	Big Data & Long Data Processing and Analysis
		Big Data & Human Decision Making
		Multi-Domain Situational Awareness
		Planning and Managing Uncertainties
	Advanced Systems Concepts	Integrated Human - Machine Hybrid Force
		Clusters & Swarms
		Modular, Scalable Systems
		High Assurance Engineering & Validation
	Autonomy	Artificial Intelligence
		Mission Autonomous Systems
		Human-Autonomous Machine Teaming
	Communications & Networks	Secure and Resilient Communications
		Trusted Multi-Domain Information Sharing
		Ad hoc and Heterogeneous Networks
PHYSICAL	Precision Engagement	Precision Control
		Weapons - Techniques and Systems
		Weapons - Effects
		Active & Passive EM, Acoustic & Optical Countermeasures
	Platforms & Materials	Fast and Agile Platforms
		Unmanned Platforms
		Hypersonic Platforms
		Advanced and Adaptive Materials
		In-Theatre Fabrication & Production of Equipment
	Power & Energy	Power & Energy Storage
		Alternative & Renewable Energy Sources
		Propulsion
		Enhanced Energy Efficiency & Management

Targets of emphasis do not naturally align with the more broadly identified EDTs nor provide sufficient resolution of potential or current development areas found within the identified EDTs. Nevertheless, they are useful for providing insights into developing a second layer to the EDT decomposition. For purposes of this report, we refer to these as Technical Focus Areas (TFA). TFAs are sub-aspects of EDTs suitable for focused research.

Technology Watch Cards (TWC)

Recognising the pressing need to maintain the Alliance's technological edge, the STO actively pursues *Technology Watch* for the Alliance. The STO Panels and Group have embraced a culture of continually identifying and documenting potentially disruptive science or technology in *Technology Watch Cards*. These cards contain assessments of the maturity of the science or technology and offer commentary on how science or technology may affect the capabilities of the Alliance and potential adversaries in the future. The current S&T Trends report relies heavily on the almost one hundred Technology Watch Cards developed by the STO Panels and Group to deliver a short synthesis of observed technology trends. TWC assessments and text were especially helpful in drafting the more detailed appendices in this report. TWC cards that have been recently developed, updated or are in the process of being updated are:

- **AVT**: · Hypersonic Vehicles · Additive Manufacturing
- **HFM**: · Digital twin of the human · Emotional design; Designing interface that takes into account emotional responses · Trust engineering
- **IST**: · Probabilistic Programming Languages · Electromagnetic Metasurfaces · Free Space Optical Communications - Communications and Networks · Self-Organising Networks - Communications and Networks · Compressive Sensing for EO-IR systems · Neuroelectronics · Intelligent Autonomy · Blockchain Technology · Digital Twins · Multi-Party Computation · Real Avatars · Quantum-safe cryptography · Quantum Technologies - Communications and Networks, Computing & Simulation, Sensing & Imaging · Blockchain and Distributed Ledger Technologies
- **SAS**: (N/A)
- **SCI**: · Alternative Computing Architectures · Integrated Defensive Aid Systems · AI & counter-AI · Sensing Systems · System V&V
- **SET**: · Cognitive EW · Early warning passive RF systems · Fully digital RF Systems · Quantum Sensing · Neuromorphic Processing · Crystal Vacancy Centre Sensors · Metal-Organic Frameworks · Space-borne Hyper-spectral Capability · Adaptive Optics · Multi-band Thermal Imagery · SWIR imagery · Remote Digital Holography · Ultrashort Laser Application for Defence and Security · Integrated RF Photonics · Deep Learning for Military EO/IR ATR
- **MSG**: · Modelling and Simulation for social media · Artificial Intelligence - Data-driven Behaviour Modelling · Immersive Simulation Devices for Improving Dismantled Soldier Reparation with Augmented and Mixed Reality Devices

As most tech watch cards are NATO UNCLASSIFIED, they are used predominately to flag areas of interest and provide contextual information. All conclusions in this report are based on open-source materials.

Von Kármán Horizon Scans (vKHS)

To address emerging challenges, the von Kármán Horizon Scans (vKHS) is an instrument to quickly perform a technology scan on a particular S&T topic within an abbreviated period (typically two to 6 months). The process assesses the state of leading-edge research in a specific S&T area, the outlook for the next decade, its relevance for the armed forces, and potential avenues for investment. They draw upon internationally recognised S&T expertise and experienced senior military. von Kármán Horizon Scans have been undertaken on laser weapons, quantum technologies, artificial intelligence, and optronic 3D imaging systems.

Workshops

From 8 to 9 February 2021, the NATO Science & Technology Organization (STO) conducted the Disruptive Technologies Table-Top Exercise (D3TX), its first fully virtual serious (public release) game to assess the military relevance and potential impact of emerging and disruptive technologies (EDTs) [33]. This ambitious event attracted over two hundred active participants from various backgrounds, including the armed forces, policy-making, procurement, defence research, academia, and industry, from Allied and many Partner Nations.

Participants of different professional backgrounds were grouped into small syndicates of eight to fourteen players. Each syndicate played within one scenario but addressed all capabilities and assessed all technologies. Further, the D3TX provided a means for exploring the operational impact of previously identified EDTs and TFA. However, it also identified innovative technology areas (so-called *weak signals*). These areas have been considered in the development of this report.

The D3TX tackled the challenging assessment of the technological impact on military operations from several different angles:

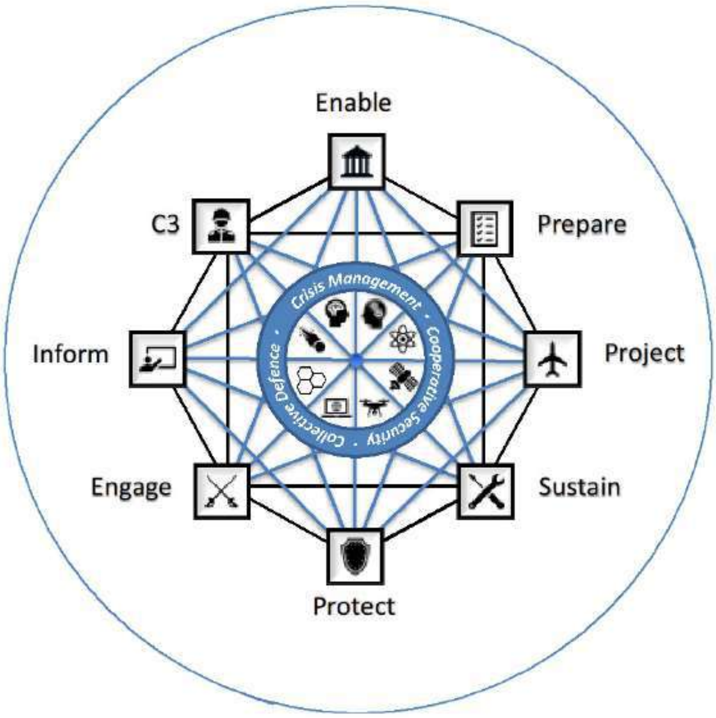


Figure 2.3: Disruptive Technologies Table-Top Exercise (D3TX) [33]

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- The D3TX was played against four bespoke scenarios that covered the full spectrum of Alliance core tasks as identified in NATO's Strategic Concept: Collective Defence, Crisis Management, and Cooperative Security.
- The D3TX addressed the comprehensive set of required military and enterprise capabilities across the land, sea, air, cyber, and space domain. The capabilities were: Enable, Prepare, Project, Sustain, Engage, Protect, C3 and Inform.
- The D3TX assessed a broad range of emerging and disruptive technologies, represented by twenty-seven Technology Cards (based on [2]), while also allowing players to identify *"weak (technology) signal"* cards.

2.3.3 Surveys

Feedback on Emerging S&T

During the spring STO panel meetings, the STO panels were asked to provide a rough assessment of which technology areas were considered emergent and disruptive. This allowed additional detail to be added to the development of the TFAs, augmenting the information derived from the TWCs. The list generated per panel:

- **AVT**: · Electric drive · Renewable energy · Single staged orbit (launch) · Energy management
- **HFM**: · Ethical, Legal and Social Implications (AI and BHET)
- **IST**: · AI · Big data analytics and visualisation · Robotic process automation · Quantum computing and algorithms · Virtual/Augmented/Extended (VR/AR/XR) reality, tele-existence and real avatars · Data-centric architecture/security · Distributed resilient infrastructure: Tactical cloud/edge computing / Heterogeneous MANET / SDN/NFE for tactical networks / cognitive radio / cognitive networks · Military Internet of Military Things · Counter/adversarial-AI and AI for cyber · Homomorphic encryption, quantum-safe crypto · Trust architectures / digital trust · Ethical, legal, societal and environmental aspects of technology by design/human-machine teaming · ICT (Information and Communication Technology) · Supply chain security (devices and materials)

- **SAS**: · Non-military/non-government leadership in tech · Blockchain · Swarm tech (cooperative autonomy) · Critical materials shortages/synthetic substitute. · State of fear · Data science · Complexity and uncertainty · Invisibility (materials) · Neuroscience, mind control · Hypersonic/autonomy combined
- **SCI**: · Alternative Computational Architectures · Quantum technologies · Ethical, legal, and social implications (aspects) with the widespread use of AI (ELSI / ELSA) · Massive or Ultra-large Systems of systems (SoS) · Self-configurable integration and interoperability · Self-Adaptive AI and Massive use of Reinforcement Learning · General Purpose Artificial Intelligence · Hyperconvergent Infrastructure · Autonomy for low-cost, attritable weapons · Offensive cyber · Multi-use autonomous defences and how does it change the air power game · Climate change – How do our systems work in a changing environment · Applications of quantum technology · Interruption of the hypersonic kill chain · Space – denial/protection · Interoperability (Standards) – managing operations in the EW spectrum · Use and democratisation of direct energy weapons (DEW) · AI · Automation · Hyperspace · AI/Automation within cyber · Human trust in autonomy
- **SET**: · Cognition and AI for RF-Sensor Technology · RF Technology for counter-UAS applications · RF and digital technology · Space Situational Awareness · Quantum Algorithms for Data Fusion · Integrated Photonic Sensing · Neuromorphic Processing · Crystal Vacancy Centre Sensors · AI for underwater autonomy exploration/sensing · Certification of AI systems · Metal-Organic Frameworks · Neuromorphic sensing · Mid-IR lasers · Quantum lidar · Photonic integrated circuits · Metalenses · Single photon counting detector arrays in the infrared
- **MSG**: · Digital Twin

EDT Survey of STO Panels

The STO network consists of approximately five thousand active science workers. A survey was prepared and distributed to all STO panels and members engaged in the research network to leverage this expertise. The survey was available in 2022 from early September to the beginning of November. It collected information on technology readiness levels, maturity forecasts and critical keywords associated with the EDTs and TFA. The survey results have provided a *wisdom of the crowd* assessment, with individuals contributing appraisals only to those EDTs for which they have experience or interest.

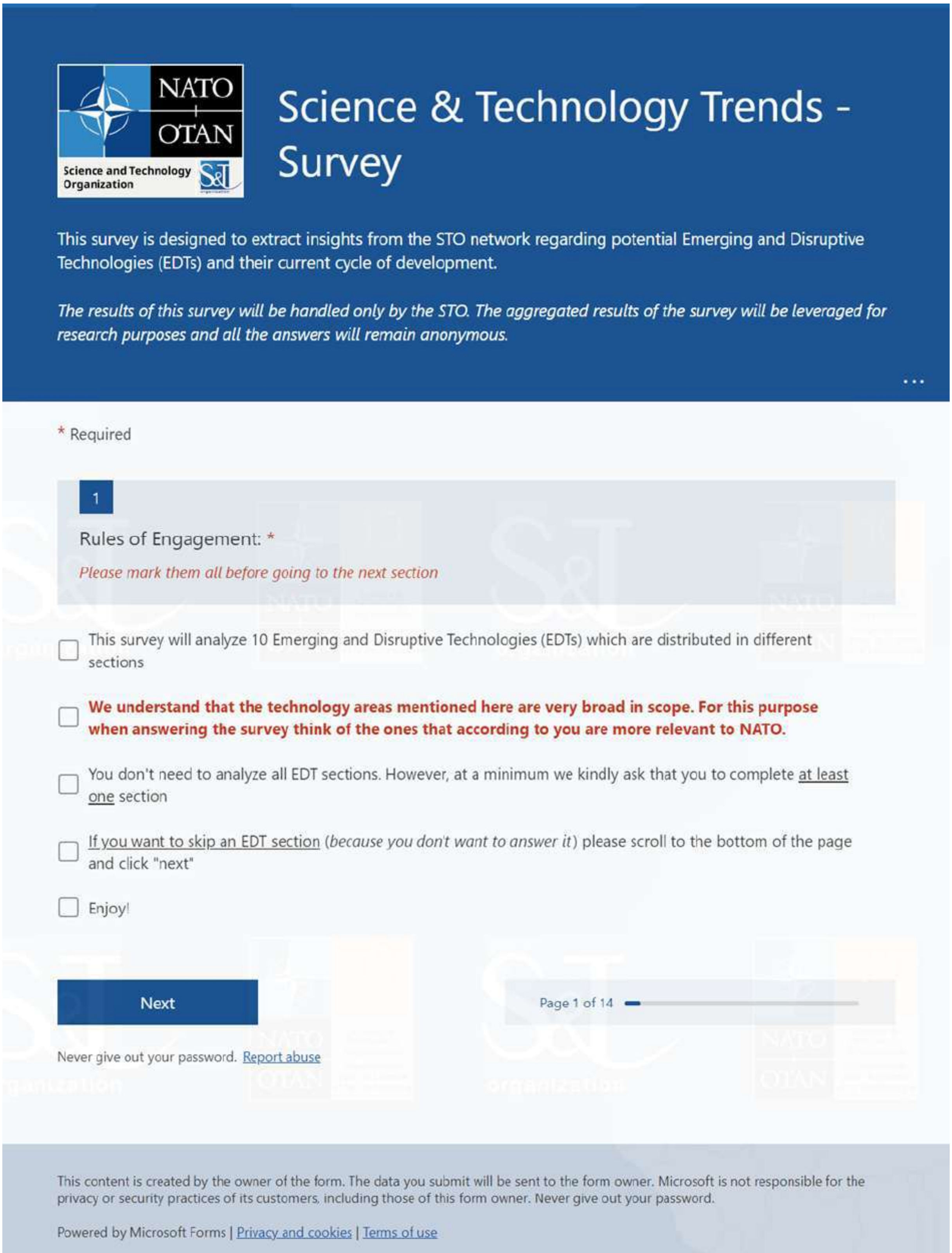
Out of approximately 5000 active participants within the STO network, approximately 8% responded to the survey. Such a response rate is considered *average* for an external survey of this type. Figure 2.5 demonstrates the assessments by EDT.

2.3.4 Reports

Over the last two years, the STO has responded to NATO leaders challenging the NATO community to improve awareness and exploitation of EDTs. In response, the STO developed a comprehensive assessment of EDTs, and their accompanying S&T ecosystem [2]. Since then, the STB, through the Office of Chief Scientist, has supplemented its earlier EDT studies, responding to NATO's Implementation Strategy for EDTs. This resulted in a series of NATO Chief Scientist reports and NATO documents (AC/323) summarising or exploring the S&T landscape. Those publicly released or unclassified reports may be found at https://www.sto.nato.int/Pages/NATO-Chief-Scientist-Reports.aspx and include studies on women in the armed forces, Quantum technologies, AI, Autonomy, human factors for special forces, CBRN, third country S&T developments and technology weak signals. In addition, STO reports such as those on biotechnologies [34] and CBRN [35] have provided unique and valuable insights into the future development of associated S&T areas.

2.3.5 Analytics

To provide a solid analytic basis for the assessment of EDTs, the NATO Office of the Chief Scientist co-developed with the NATO Communications and Information Agency (NCIA) the S&T Ecosystem Assessment Model (STEAM) [Figure 2.6]. STEAM is hosted by the NATO software factory and is an AI-enabled analysis tool that assesses various published reports, journal articles and pre-prints to explore current trends, collaboration, national focus, and research interests. The system pulls from over 7 million documents and 200 million abstracts, providing a *representative* sampling of current research activities over the last five years. The underlying data is pulled from Microsoft Academic [36], arXiv [37] (Physics,



Science & Technology Trends - Survey

This survey is designed to extract insights from the STO network regarding potential Emerging and Disruptive Technologies (EDTs) and their current cycle of development.

The results of this survey will be handled only by the STO. The aggregated results of the survey will be leveraged for research purposes and all the answers will remain anonymous.

* Required

1

Rules of Engagement: *

Please mark them all before going to the next section

- [ ] This survey will analyze 10 Emerging and Disruptive Technologies (EDTs) which are distributed in different sections
- [ ] **We understand that the technology areas mentioned here are very broad in scope. For this purpose when answering the survey think of the ones that according to you are more relevant to NATO.**
- [ ] You don't need to analyze all EDT sections. However, at a minimum we kindly ask that you to complete at least one section
- [ ] If you want to skip an EDT section (*because you don't want to answer it*) please scroll to the bottom of the page and click "next"
- [ ] Enjoy!

Next

Page 1 of 14

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Figure 2.4: *Microsoft Forms Survey of STO network on S&T trends.*

EDT Survey Response

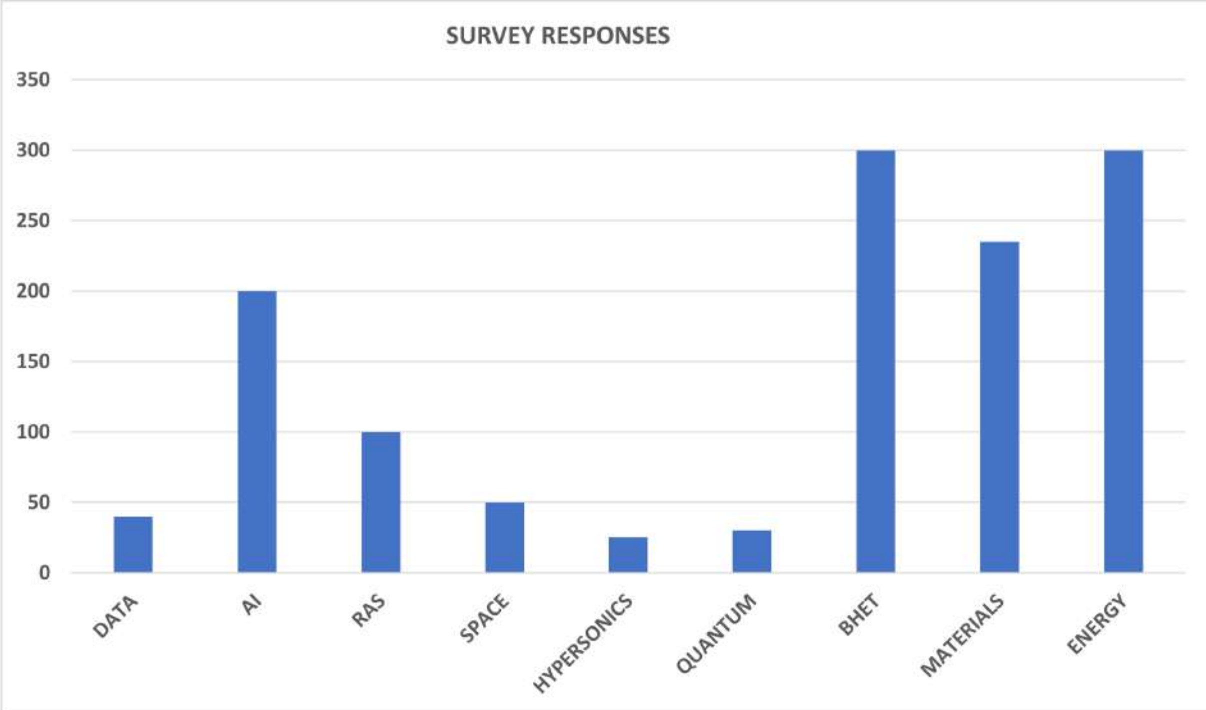


Figure 2.5: *Responses by EDT from the STO EDT Survey.*

Mathematics, Statistics, Computer Science, Electrical Engineering, Economics, Quantitative Biology, Quantitative Finance), MedRxiv [38] (Medicine) and bioRxiv [39] (Life Sciences). In addition, the integration of new sources (such as patent data) and reports (e.g. PLOS (the Public Library of Science) [40]) is being evaluated for use in future analyses. Nevertheless, STEAM is still a work in progress, with its analysis more indicative than definitive, especially given the lack of non-English language sources.

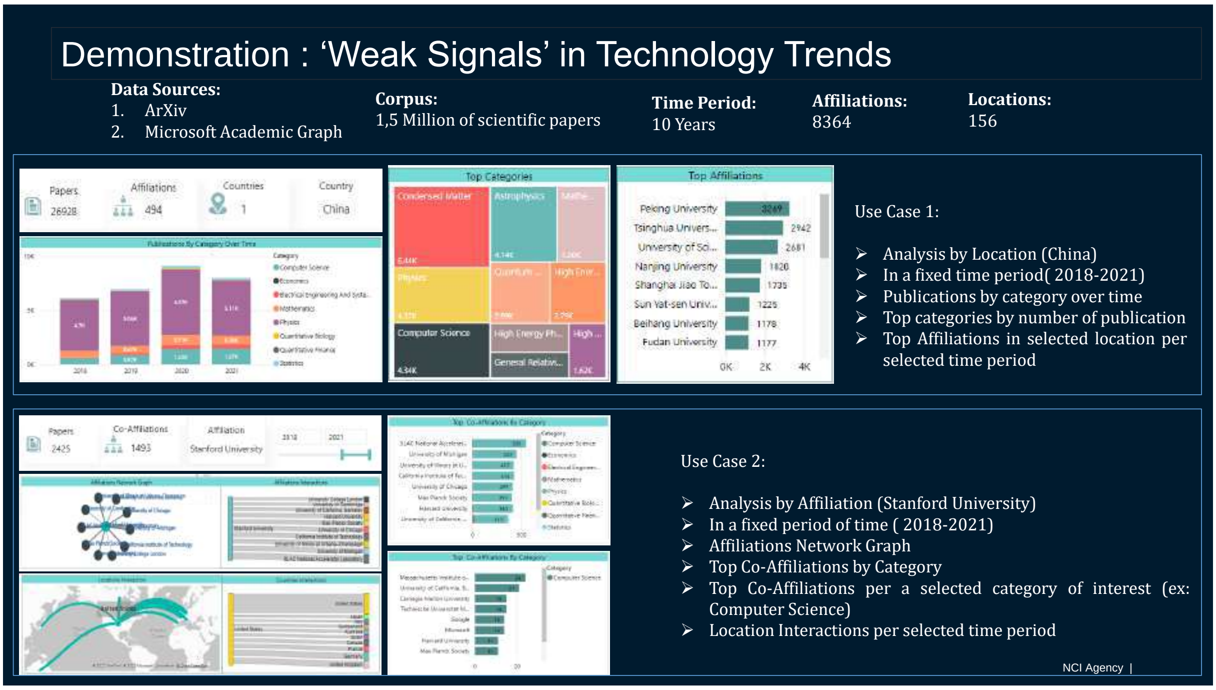


Figure 2.6: *Early Demonstration of S&T Ecosystem Assessment Model (STEAM) Use Cases.*

2.4 Alliance and Partner Research Programmes

Most STO-sponsored S&T activities are undertaken through national collaborative research activities. The STO maintains cross-alliance visibility on national research activities and priorities. These activities provided insights into emerging technology areas and activities of importance to the Alliance. In particular, the following research programs and S&T strategies were of considerable value in understanding national stretch objectives in defence and security S&T: Australia [41], US (DARPA) [42], UK [43] and France [44].

In addition, several countries have developed lists of emerging and disruptive technologies. Two recent US lists of particular value were [14] and [15]. The first list provides the following breakdown and reflects a whole-of-nation perspective:

- **Advanced Computing**: · Supercomputing · Edge computing · Cloud computing · Data storage · Computing architectures · Data processing and analysis techniques
- **Advanced Engineering Materials**: · Materials by design and material genomics · Materials with new properties · Materials with substantial improvements to existing properties · Material property characterisation and lifecycle assessment
- **Advanced Gas Turbine Engine Technologies**: · Aerospace, maritime, and industrial development and production technologies · Full-authority digital engine control, hot-section manufacturing, and associated technologies
- **Advanced Manufacturing**: · Additive manufacturing · Clean, sustainable manufacturing · Smart manufacturing · Nanomanufacturing
- **Advanced and Networked Sensing and Signature Management**: · Payloads, sensors, and instruments · Sensor processing and data fusion · Adaptive optics · Remote sensing of the Earth · Signature management · Nuclear materials detection and characterisation · Chemical weapons detection and characterisation · Biological weapons detection and characterisation · Emerging pathogens detection and characterisation · Transportation-sector sensing · Security-sector sensing · Health-sector sensing · Energy-sector sensing · Building-sector sensing · Environmental-sector sensing
- **Advanced Nuclear Energy Technologies** · Nuclear energy systems · Fusion energy · Space nuclear power and propulsion systems
- **Artificial Intelligence**: · Machine learning · Deep learning · Reinforcement learning · Sensory perception and recognition · Next-generation AI · Planning, reasoning, and decision making · Safe and secure AI
- **Autonomous Systems and Robotics**: · Surfaces · Air · Maritime · Space
- **Biotechnologies**: · Nucleic acid and protein synthesis · Genome and protein engineering, including design tools · Multi-omics and other biometrology, bioinformatics, predictive modelling, and analytical tools for functional phenotypes · Engineering of multicellular systems · Engineering of viral and viral delivery systems · Biomanufacturing and bioprocessing technologies
- **Communication and Networking Technologies**: · Radio-frequency (RF) and mixed-signal circuits, antennas, filters, and components · Spectrum management technologies · Next-generation wireless networks, including 5G and 6G · Optical links and fibre technologies · Terrestrial/undersea cables · Satellite-based communications · Hardware, firmware, and software · Communications and network security · Mesh networks/infrastructure independent communication technologies
- **Directed Energy**: · Lasers · High-power microwaves · Particle beams
- **Financial Technologies**: · Distributed ledger technologies · Digital assets · Digital payment technologies · Digital identity infrastructure
- **Human-Machine Interfaces**: · Augmented reality · Virtual reality · Brain-computer interfaces · Human-machine teaming
- **Hypersonics**: · Propulsion · Aerodynamics and control · Materials · Detection, tracking, and characterisation · defence
- **Networked Sensors and Sensing**: · Not available

- **Quantum Information Technologies**: · Quantum computing · Materials, isotopes, and fabrication techniques for quantum devices · Post-quantum cryptography · Quantum sensing · Quantum networking
- **Renewable Energy Generation and Storage**: · Renewable generation · Renewable and sustainable fuels · Energy storage · Electric and hybrid engines · Batteries · Grid integration technologies · Energy-efficiency technologies
- **Semiconductors and Microelectronics**: · Design and electronic design automation tools · Manufacturing process technologies and manufacturing equipment · Beyond complementary metal-oxide-semiconductor (CMOS) technology · Heterogeneous integration and advanced packaging · Specialised/tailored hardware components for artificial intelligence, natural and hostile radiation environments, RF and optical components, high-power devices, and other critical applications · Novel materials for advanced microelectronics · Wide-bandgap and ultra-wide-bandgap technologies for power management, distribution, and transmission
- **Space Technologies and Systems**: · On-orbit servicing, assembly, and manufacturing · Commoditised satellite buses · Low-cost launch vehicles · Sensors for local and wide-field imaging · Space propulsion · Resilient positioning, navigation, and timing (PNT) · Cryogenic fluid management · Entry, descent, and landing

The second list provides a more defence-oriented perspective:

- **Seed Areas of Emerging Opportunity**: · Biotechnology · Quantum Science · Future Generation Wireless Technology (FutureG) · Advanced Materials
- **Effective Adoption Areas**: · Trusted AI and Autonomy · Integrated Network Systems-of-Systems · Space Technologies · Renewable Energy Generation and Storage · Advanced Computing and Software · Human-Machine Interfaces
- **Defence-Specific Areas**: · Directed Energy · Hypersonics · Integrated Sensing and Cyber

Similarly, the European Union conducts technology trends assessments through the European Defence Agency and European Commission. In particular, the European Commission (EC) Joint Research Center (JRC) annually evaluates emerging and disruptive technologies, determined through workshops and analysis of publications and patent data. The latest in these reports may be found in [16].

- **Medicine & Biotechnology**: · BiSCaO antiseptics · CELMoDs for cancer · Chemodynamic therapy · CRISPR-based diagnostics · Direct RNA sequencing · DIY artificial pancreas · eCIRP · Facial genotyping · FAPI PET/CT · Firibastat · Flash radiotherapy · Flualprzolam · Heritable human genome editing · Inebilizumab · Intravascular Lithotripsy · Mavacamten · Molnupiravir · Nanocatalyst cancer therapy · Soluble immune checkpoints · Spatial and temporal omics · Urobiome
- **Engineering & Physics**: · Atomic-scale manufacturing · Autonomous surface ship · Gas chromatography-ion mobility · Nanoparticle exosolution · Optoelectronic synapses · Passive radiative cooling · Rotating detonation rocket engine · Space-air-ground integrated network · Spintronic terahertz emitter · Twistronics
- **Materials**: · Eutectogel · High entropy carbides · Hybrid nanofluid · Ionic skin · Kagome superconductors · Martian concrete · Monolayer MA2Z4 · Monolayer tellurne · Mycelium-based materials · NB2CTx mxene · Nickelate superconductor · Orgonohydrogel · Quantum metasurfaces · Twin graphene · Twisted bilayer graphene · Ultrawide bandgap semiconductor · V2CTx Mxene
- **Energy**: · Aqueous Al ion batteries · Calcium batteries · Dendrite-free Zn battery · Hydrovoltaics · Mg metal batteries · Multi-energy microgrids · Potassium metal batteries · Sodium CO2 batteries · Zinc CO2 batteries · Zinc-organic batteries · Zinc ion capacitor
- **ICT - Information and Communication Technologies**: · 3D multi-object tracking · Cognitive digital twin · Directed Acyclic Graph blockchain · DNS-over-HTTPS · Dual blockchain · Wearable computing · Edge artificial intelligence · External Human-Machine Interfaces · Few-shot object detection · Fog robotics · Health chatbot · Human digital twin · Internet of space things · Programmable wireless environments · Unpaired image translation · Versatile video coding · Wireless time-sensitive network
- **Agriculture & Environment**: · Agrophotovoltaics · Biomass chemical looping gasification · Interfacial solar evaporators · Microplastics removal · Nanoagriculture · Nanofertilisers · Plasma agriculture · Plastic chemical upcycling

- **Societal Issues**: · AI ethics · Fake news detection · Green AI · Misinfodemics · Peer-to-peer energy trading · Real-world clinical outcome

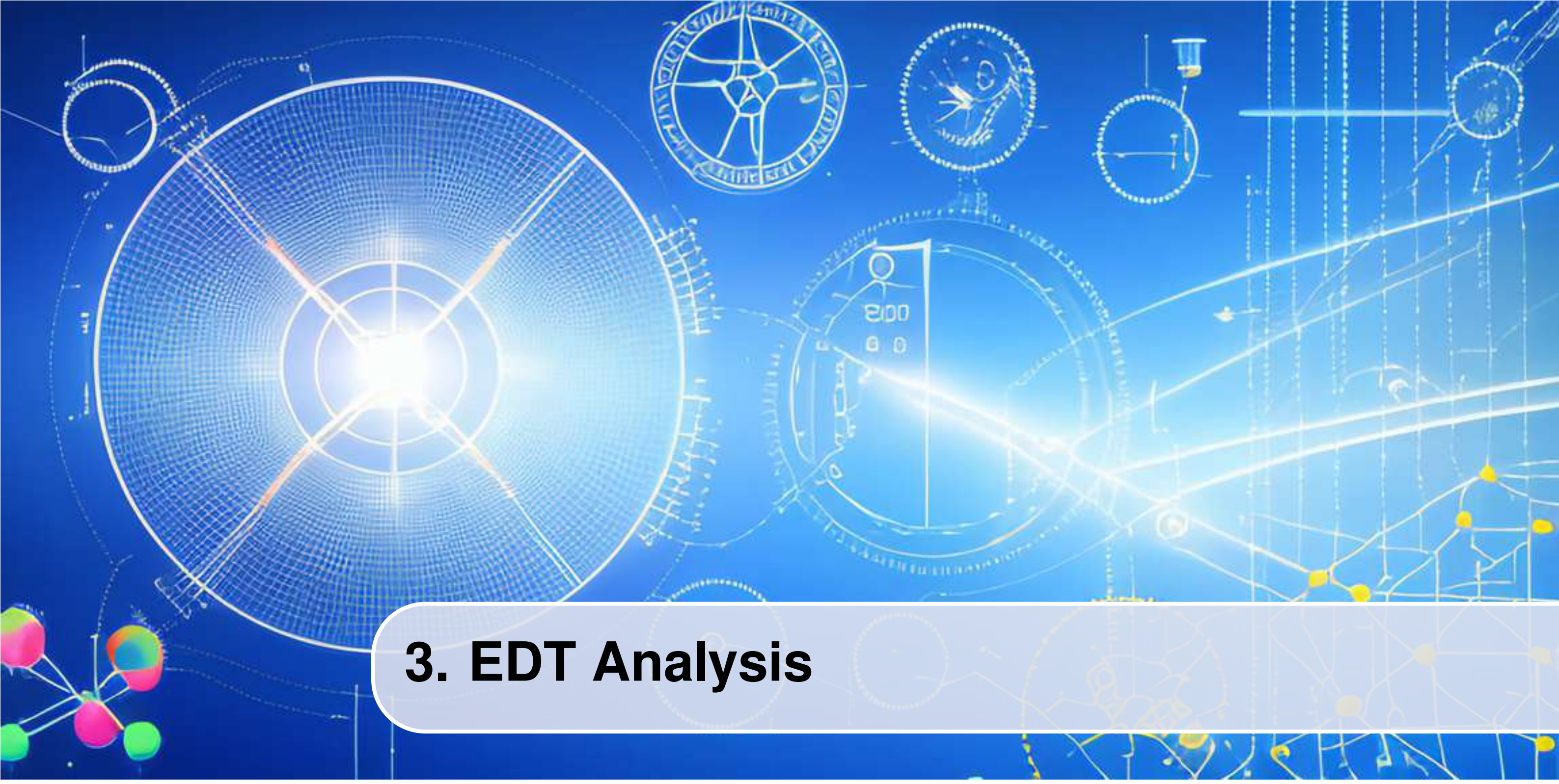
Further, the European Defence Agency (EDA) has a structured approach to developing research areas through the Capability Technology Areas (CapTechs) and the Overarching Strategic Research Agenda (ORSA) Technology Building Blocks (TBB) [45, 46]. A slightly modified, expanded and consolidated version is shown below:

- **Air** · Autonomous Air Vehicle Operation · Cooperative Air Vehicle Operation · Detect, Sense and Avoid Systems · System Diagnostics, Fault Prognostics, and Self Repair · Human-Machine-Interface and Cognitive Ergonomics · Propulsion, Power Generation and Distribution · Secure Command and Control Systems · Rotorcraft Next Generation High-Performance Vertical Lift · Fixed Wing
- **Missiles and Munitions** · Munition Life Management · Insensitive Munitions · Fuzing and Ignition Systems · Precision Guided Munition and Missiles · High-Performance Gun Launch and missile propulsion · Railgun weapon · Improved tools and methods for qualification and safety · IED Detection and Defeat Technologies · High-performance, low-sensitivity and REACH-compliant energetic materials · Improved Warhead and Penetrator design · Pyrotechnics for Decoying and Obscuring · New Production Techniques for Munition Components · Education and Training for Ammunition Technologies
- **CBRN & HF** · Human Autonomy Teaming · Human Performance Monitoring & Enhancement · Customised Training · Integration of human clothing and equipment in platforms · Personal Protective Equipment · Detection, Identification and Monitoring (DIM) of CBR · CBRN Hazard Management · CBRN modelling and simulation · Protection of Critical Infrastructure (PCI) from CBRN · Protection of food and water supply from CBRN · Assessment, Diagnosis, and Medical Countermeasures of CBR Hazards · Human Resources & Social Sciences
- **Components** · RF Photonics · IR imaging Detector & sources · Terahertz detectors & sources · Microwave Power · RF Transceiver modules · Enabling Components for Advanced Antennas · ADC & DAC · Signal Generation and Time Reference · System-on-Chip · High voltage SiC devices and related energy storage for pulsed power applications · Defence critical technologies supply chain · Advanced Packaging, PCB and Thermal Management Technologies
- **Cyber R&T** · Cyber Defence Situation Awareness · Cognitive Science with cyber implications · Convergence between Cyberoperations and Electronic Warfare · Cross-cutting cyber defence for land, maritime, air and space · The protection of military communications and information systems · Quantum computing and cryptography with cyber implications · Autonomous cyber response capabilities · Modelling and Simulation for Cyber defence
- **Energy** · Alternative fuels and drive/propulsion systems · Energy storage: electrical, electrochemical, mechanical, structural and thermal · Engine and power distribution system efficiency technologies · Energy management technologies: innovative and efficient systems · Solar energy generation (thermal and electrical generation) · Militarisation of environmental technologies: water, wastewater and energy from waste · Energy harvesting/scavenging · Wind energy · Energy and environment technology systems integration
- **Information** · Management and Processing Information from Heterogeneous Sources · Coalition Network Security and Protection and Interaction with commercial technologies · Cognitive Radio · Tactical Cloud Infrastructure for C4ISR Systems · Electronic Support Measures (ESM) for Communications · Internet of Things (IoT) for Defence · Information Process Enhancement by using AI and Big Data · Long Range Communication · Software Defined Networking (SDN)
- **Land** · Land Systems Architecture & Integration · Power generation, storage and management for Land Systems · Passive and active protection for land Systems · Less-than-lethal effectors · Manned/unmanned teaming, adaptive cooperation between manned and unmanned systems with different levels of autonomy · Target / Threat recognition and identification · Health and Usage Monitoring · Novel User Interfaces for Soldier – Assets integration/control · Mobility and Counter-Mobility · Weapon system integration
- **Materials** · Light Weight for High-Performance Structures · Materials, structures for Protection Against Military Threats · High-temperature materials · Camouflage and signature management technologies · Emerging materials for future platforms · Materials, structures & concepts for platform monitoring · New manufacturing, joining and repair processes · Surface engineering for maximum lifetime and hostile environments · Advanced and smart textiles for soldier systems and platforms · Computational Design and materials modelling

- **Maritime** · Communication and distributed sensor networks, surface and underwater · Simulation and Training · Platform Survivability and Operability in challenging conditions · Energy and Propulsion · Increased Autonomy and Robotics · Identifying and Countering Threats, High-Energy Weapons Integration · Smart Industrialisation and Predictive Maintenance
- **Navigation** · Navigation in GNSS denied environment · Position, Navigation and Timing (PNT) superiority and integration in operations and systems · Guidance and control in challenging environments · Autonomous and automated GNC and decision-making techniques for manned and unmanned systems · Fault tolerance control (FTC) · Multi-Robot control and cooperation · Precision guidance and control of weapons · Key enabling and performance enhancing GNC technologies
- **Optronics** · Hyperspectral/multispectral Imaging System · Passive Imaging Systems · Novel optical configuration · Active Imaging System · Image enhancement · Image processing · EO Countermeasure systems · Laser Weapon System · Modelling and simulation · Data fusion and system integration
- **Radar** · Detection, Tracking and Recognition of Challenging Targets · Advanced front/back end · Electronic Warfare · Multi-Platform RF Systems · Cognitive Radars · Scalable Multi-function RF Sensors (SMRF) · Specific Radar Applications · Disruptive Concepts · Common EU Benchmarks for Validation, Verification and Standardisation
- **Simulation** · Integrated Live, Virtual and Constructive (I-LVC) for Training, Simulation and Serious Games Solutions · Artificial Intelligence (AI) and Big Data (BD) for Decision-Making Support · Immersive, Virtual and Augmented Reality · Cyber Defence Simulation · Joint Strategic, Operational and Tactical level simulators · Modelling & Simulation as a Service (MSaaS) for the synthetic environment and rapid scenario generation · Simulation for Systems of Systems (S3) · Recognised Space Picture (RSP) · Defence Satellite Reconnaissance Systems
- **Space** · Architecture & Policy · Earth Observation & Reconnaissance · Space Situational Awareness (SSA) & Space Operations · Positioning, Navigation and Timing (PNT) · Satellite Communications · Quantum and other Disruptive Technologies · Data & Signal Processing for Decision-Making · Launch, Space & Ground Segment Technologies · Protection

2.5 MetaStudies, Articles and Reports

Many nations, academic and commercial interests are involved in research or developing reports on future (science &) technology trends or strategic foresight. This report draws on a diverse collection of journals, newspapers, magazines and web sources identified and consolidated through various news aggregators and independent research. Major foresight studies also provide a core foundation for this report. Of particular use in the drafting of this report were the 2022 Gartner Hype Cycle for Emerging Technologies [24], Deloitte Insights - 2022 Tech Trends [47], Future Today Institute Tech Trends 2022 [48], OECD Science, Technology and Innovation Outlook 2021 [49], Imperial TechForesight [50], The Report of the Commission on the Geopolitical Impacts of New Technologies and Data (North Atlantic Council - Geotech Center) [51], Articles from the NATO Defence College (e.g. [52, 53, 54, 55]), Congressional Research Service Reports such as [56, 67, 76, 80, 81, 82, 83, 84, 85, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 63, 68, 69, 70, 71, 72, 73, 74, 74, 75, 77, 77, 78, 79], Federation of American Scientists [86], European Parliament [87], RAND reports [88, 89, 90], UNESCO Science Report [91], World Economic Forum [92], Brookings [27], and summaries of international technology forecasts found in [93]. For AI and the development of STEAM, the *Center for Security and Emerging Technologies* (CSET) [94] at Georgetown University's Walsh School of Foreign Service was an especially valued source of information and insights.



3. EDT Analysis

3.1 Description

This volume has separate appendices that provide a more detailed exploration of each EDT, drawing heavily upon STO research and technology watch activities, quantitative analysis, surveys, serious games and expert opinion. This section also includes *Conjecture Cards*, short vignettes that describe the potential future application or potential consequences of these technologies. They are included to help contextualise the potential impact of these technologies.

Each appendix follows a set structure:

- **Title**: A short title for the EDT.
- **Quote**: These provide context for the discussion.
- **Definition**: A useful definition of the EDT in question. Where appropriate, these are drawn from approved NATO or national sources, although they may be expanded as necessary to describe the EDT in question.
- **Keywords**: Useful keywords that may aid independent topic exploration.
- **Overview**: An expansive overview of the EDT in question. It is broken into sub-sections representative of the technical focus areas (TFA), or if you prefer, a second level representing important sub-aspects of the EDT.
- **Military Implications**: A consideration of how this EDT will impact NATO's (e.g. BLUE) operational and enterprise capabilities (Enable, Prepare, Project, Engage, Protect, Sustain, Inform, C3). This is followed by discussing the unique implications for forces or groups (e.g. RED) that may threaten NATO and Alliance nations.
- **Interoperability**: Discusses the EDT's interoperability and standardisation challenges.
- **S&T Development**: Explores the implications of developments in this EDT on the other EDTs (e.g. *Data* as it enables developments in AI).
- **STO Activities**: A sampling of current STO activities relevant to this EDT.
- **STEAM**: Publication Keywords. Given the shear volume of charts created a separate limited distribution report will be developed at a later date covering all EDTs and TFAs showing: keywords,

national technology leadership, publication trends, institutional leadership and institutional collaboration. Appendix L provides an example of these charts and Volume 1 of this report provides a sub-set for EDTs only.

- **Survey**: Simplified Table of Impact, TRL and Horizon. Appendix K provides a comprehensive assessment of the survey results showing: Keywords (Word Cloud), Impact Assessment, TRL Assessment and Horizon Assessment.
- **Conjecture Cards**: Representing small vignettes designed to stimulate discussion or support the development of a technology futures (serious) game.

3.2 Exploration of Selected EDTs

As of 2022, there are nine canonical EDTs and one additional for the purposes of this report. These are in alphabetical order:

- **AI**: Artificial Intelligence (Appendix A).
- **Autonomy**: Robotics and Autonomous Systems (Appendix B).
- **BHET**: Biotechnology and Human Enhancement (Appendix C).
- **Data**: Big Data and Information Communication Technologies (Appendix D).
- **E&EM**: Electronics and Electromagnetics (new supplemental EDT) (Appendix E).
- **Energy**: Energy and Propulsion (Appendix F).
- **Hypersonics**: Hypersonic Technologies (Appendix G).
- **Materials**: Novel Materials and Advanced Manufacturing (Appendix H).
- **Quantum**: Quantum Technologies (Appendix I).
- **Space**: Space Technologies (Appendix J).

Two additional appendices follow these:

- **STO Experts Survey**: An analysis of the STO-wide survey on the state, rate, and impact of EDTs (Appendix K).
- **S&T Analysis Model (STEAM) Results**: A sample analysis of the EDTs using the S&T Ecosystem Analysis Model (Appendix L).

4. Conclusion

Technology and Society

"If you make a great number of predictions, the ones that were wrong will soon be forgotten, and the ones that turn out to be true will make you famous." - *Malcolm Gladwell* [95]

Mastering the R&D, concept development, and military application of EDTs will expand NATO's ability to respond at an enterprise level and support multi-domain operations. However, the prediction of militarily relevant S&T developments over a twenty-year period is non-trivial. To do so, the STO has drawn from various data sources, analytical methods, and expert opinions to outline a realistic estimate of the state, rate of development, and impact of EDTs.

Ultimately, this report has outlined how EDTs will disrupt, degrade, and enable NATO military capabilities in the 2023-2043 timeframe. Understanding *why* they present a problem or opportunity, *how* they are expected to manifest, and *what* this will mean to the Alliance is an excellent first step and will help ensure NATO remains technologically prepared and operationally relevant.

Appendices

A. Artificial Intelligence

Artificial Intelligence

"We have to improve scientific understanding amongst AI paradigms so as to build AI that benefits humanity and the planet. The world will need a principled AI education for all, since AI will be the key technology of the next decades, if not the XXI century." - *Luis Lamb* [96]

Definition

Artificial Intelligence (AI)

AI refers to systems that display intelligent behaviour by analysing their environment and taking actions – with some degree of autonomy – to achieve specific goals. AI-based systems can be purely software-based, acting in the virtual world (e.g. voice assistants, image analysis software, search engines, speech and face recognition systems). Alternatively, AI can be embedded in hardware devices (e.g. advanced robots, autonomous cars, drones or Internet of Things applications) [97].

Keywords

Artificial Intelligence (AI) · Machine Intelligence · Deep Learning (DL) · Machine Learning (ML) · Artificial Neural Networks (ANNs) · Machine Learning (ML) · Expert Systems · Semantic Analysis · Supervised Learning · Unsupervised Learning · Reinforcement Learning · Clustering · Deep Fakes · Machine Vision · Chat-bot · Decision Trees · Data Science · Genetic Algorithm · Autonomy · Artificial General Intelligence (AGI) · Responsible Artificial Intelligence (RAI) · Generative Adversarial Networks (GANs) · Explainable AI (XAI) · Observable AI · Trust · Trustworthiness · AI Robustness · Resilience · Generative Adversarial Network (GAN) ·

Developments

Overview

Since the publication of the last NATO S&T trends report [2], Artificial Intelligence (AI) has evolved rapidly and in surprising directions across multiple domains [98]. At the same time, AI's wide and imaginative application has created a climate of increased expectations regarding its possible implementation.

The intrinsic value of AI and machine learning is centred on its predictive capabilities. However, to extract these technologies' full potential, organisations must restructure and evolve [98].

It is worth mentioning that currently, AI presents some technical inefficiencies, limitations, and human-trust issues concerning its underlying methodology, which are becoming more obvious due to its increasing use. AI's large and diverse applications are game-changers that must still be enabled by appropriate methodologies (e.g. AI methods). The growing need to reduce disparities is a weak technology signal that indicates how the application of divergence methods will potentially lead to the next AI winter in 5-10 years [2].

For this appendix, AI is understood to encompass four main areas of R&D activity, which are seen to be disruptive: **(1) AI Methods**; **(2) AI Application**; **(3) M-M Symbiosis**; and, **(4) Resilience**. Breakthroughs in these areas will correct and reduce divergences, drive increased adoption, and enhance the robustness, utilization, and reliance on AI across the Alliance and with potential adversaries.

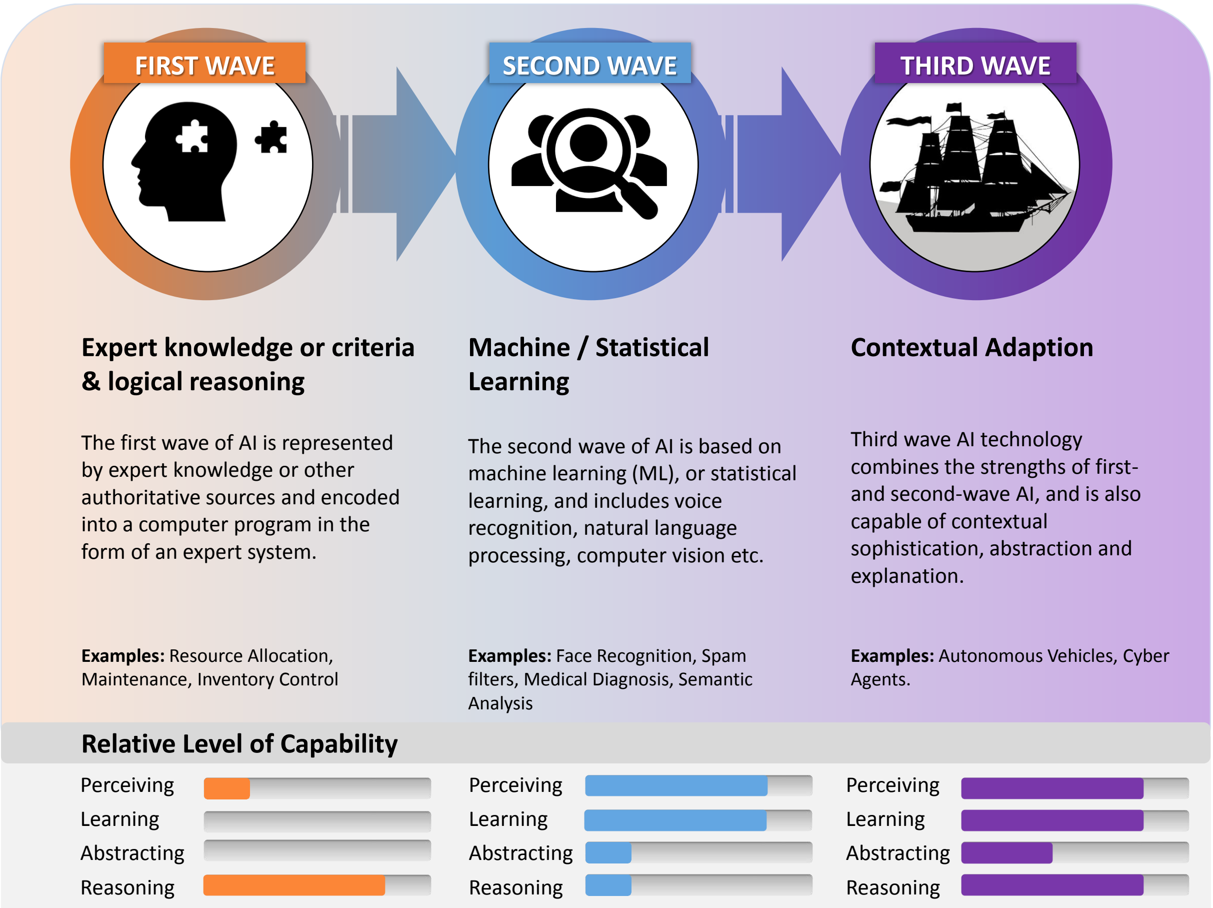


Figure A.1: *The Three Cycles of AI (CREDIT: Adapted from [99]).*

The AI was conceptually envisaged before 1900 [99], and it has undergone three main cycles of technological and scientific development [100] (See: A.1):

- **Expert or (handcrafted) knowledge-based AI:** This first cycle compiles AI's embryonic knowledge-based state grounded in experts' rules-based decision-making approaches (e.g. hard-coded if-then statements, decision trees, Boolean and fuzzy logic), which constrain systems reasoning and learning abilities.

- **Data-based AI (statistical Learning):** The second cycle advances AI systems by developing and applying statistical methods trained on (pre-labelled) data for specific purposes. Those methods include *Machine Learning (ML)* and *Deep Learning (DL)*, which offer a wide array of techniques and introduce logic-senses and (auto-)learning abilities (e.g. supervised, unsupervised and reinforcement Learning). These second-wave systems rely heavily on the data they have been fed and trained on.

- **New or next-generation of AI (contextual adaptation):** Currently, the third wave (or Neurosymbolic [101]) AI presents considerable developments in sensing and perception abilities enabling contextual systems adaptation. It has been characterised by ubiquitous intelligent (or autonomous) systems (also called embedded-AI), bio-, and human-inspired learning methods (e.g. artificial neural networks such as deep and machine Learning) [99].

Nowadays, the development of AI is still characterised by *"hype and bluster"* [100]. AI technology is considered a scientific area of development largely attracting national attention; and a (general-purposes) technology with extensive dual-use for military and civilian applications [86, 102, 103]. Its wide array of applications spans from cognitive augmentation to multi-domain operations platforms, continuing with embodied AI (robotics) and advanced algorithms. AI offers an unprecedented opportunity to strengthen NATO's technological edge and will support the Alliance in fulfilling its three core tasks [104]. However, increased reliance on AI capabilities will also expand the threats the Alliance will face.

Figure A.2: *Neurosymbolic AI*

Over the next 20 years, AI will continue to play a significant disruptive role through its impact on several areas [2], such as:

- Exploitation of (very) large data sets, including publicly available data for system training and development;
- Widespread deployment and use in cyber-physical systems;
- Novel areas of application, driven by greater investment in and wider adoption of AI techniques;
- Decision making and optimal control (e.g. speed, power systems, investment, etc.);
- Computation, such as advances in everywhere/edge computing, ubiquitous sensors, database design, developmental tools, cloud computing, new algorithmic approaches and using AI to bootstrap the development of AI; and,
- Development of advanced large data analysis tools and computer vision.

However, the limitations of AI become more obvious (Figure A.3) as its deployment expands. Brittleness jeopardises AI systems' performance and reliability in simulation and training (e.g. different model settings or data inputs, uncertain or new scenarios). Unpredictable AI systems are further exposed to data poisoning and adversarial attacks leading to systems failures and malfunctions [105]. Moreover, the rationale behind any AI/ML recommendations can be opaque (e.g. AI *"Black-box"* [106]). This lack of transparency harms the development of trust in Human-Machine (H-M) symbiosis and teaming relationships. Stressing the need to revisit the mathematical, algorithmic, and technical foundations of the enabling science [105]. The lack of acknowledgement of the pitfalls is usually characterised by *unintended*, *intelligence* or *automation bias* [107], leading military and political decision-makers and operators to unfounded-misplaced trust, mistrusting and over-relying on flawed AI systems. In addition, the lack of transparency reduces the tractability of data sources and can ultimately impact attack detection [105]. Thus leading to concerns about the malicious use of AI and the return to an *"AI winter"* [2].

On the other hand, considering the global attention that AI is getting in both the private and public sectors, AI has been compared to the introduction and proliferation of electricity as a transformative technology [103, 108]. Similar to nuclear weapons proliferation in history, as argued by [109], this could raise security concerns as the Sino-US competition escalates, potentially shifting global powers.

Opposing views [107] argue that the fierce competition over AI does not constitute a security dilemma. Still, policymakers should mind the technological and political risks associated with AI and its competition.

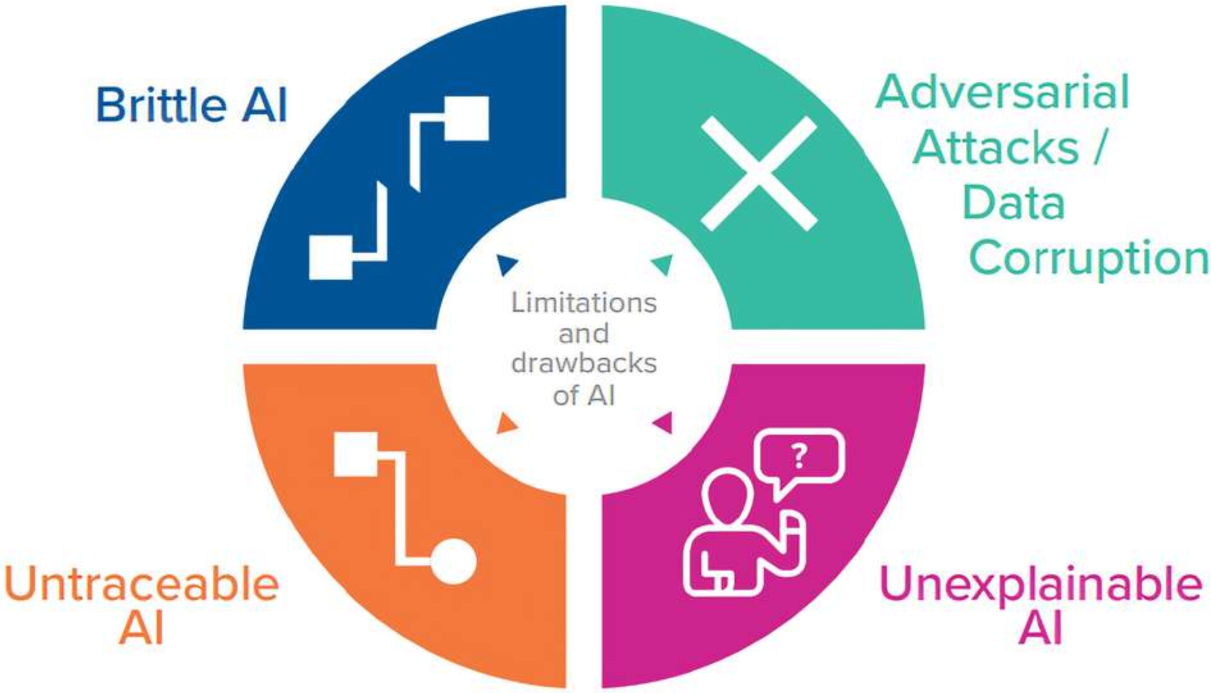


Figure A.3: Understanding AI's limitations and drawbacks (CREDIT: [105]. Lower right icon created by Ranah Pixel Studio).

Some of these risks include the Sino advance, diffusion and dissemination of Chinese technology standards in AI systems and the global market. Hence, posing a security concern and opening the door to technology standard competition, patent protection, lawfare and (design) policy writing. Consequently, stressing the need for checks and balances towards a more democratic AI, ethical, legal and moral (ELM) use and responsible use of AI (RAI). This calls for international (military) agencies, DoDs and governments to cooperate and regulate AI, or at least to define a shareable ethical vision and responsible criteria for its use [110] [1]. To mention a few attempts, the European Data Act (as the first deliverable under the European Strategy for Data) and AI Strategy, NATO Summary AI Strategy and its Principles of Responsible Use (PRU) [104, 111, 112, 113].

Much has been written on the growth of AI and its importance for the fourth industrial revolution [103, 114, 115], as AI is a critical enabler for other scientific and technology areas [103] - see Figure A.5. In addition, new developments and leaps concentrate on compiling current knowledge and advancing new learning techniques while enhancing the robustness, generalisation and trustworthiness of AI systems [101]. Furthermore, research on advancing Man-Machine Symbiosis (or Human-Machine Teaming), explainable AI (XAI), hybrid AI techniques, and advanced training methods are at the forefront in the defence and security sphere.

Advanced AI

R&D in this area began with early narrowed AI expert systems compiling rules-based approaches, often confined by human experts' knowledge of mathematical and statistical models (e.g. linear algebra, linear and multiple regression). Machine-Learning (ML), natural language processing (NLP) and Computer Vision in AI-based systems, currently applied and known as "weak or narrow" AI, soon complemented these developments. Further improvements in ML and learning infrastructures lead to the second wave of AI developments.

Advanced algorithms perform on a learning spectrum (supervised, semi-supervised and unsupervised learning, as well as transfer learning) based on the Algorithm's ability to label and cluster data identifying

[1] The OECD offers a live comprehensive repository and update of AI-related policy information, OECD's strategies and policies from 44 countries and the EU (https://oecd.ai/en/dashboards/overview)

inner-data patterns. Thus, enhancing perception while introducing the ability to learn and infers context at the cost of reasoning abilities. Downturns are addressed in the third cycle of AI, also called "next generation", combining elements of both prior waves towards general artificial intelligence (GAI).

Critical areas of research and key points are:

- **Linear Algebra** [116]
- **Linear Regression**
- **Logistic Regression**
- **Artificial Neural Network (ANN)**
- **Convultional Neural Network (CNN)** (Residual Networks, Conv1x1, Inception, UNet Dropout, Batch Normalization, Global Pooling, Auto Encoder, Generative Adversarial Network (GAN), Transfer Learning) [117, 118, 119, 120]
- **Hierarchical Recurrent Neural Network (HRNN)** (TanH, Sigmoid, LSTM, GRU, Bidirectional Recurrent Neural Network (RNN), Seq2Seq, Mechanism of attention, Transformers) [119, 121]
- **Deep Learning (DL)** (hybrid architectures, Fractal Networks)
- **Machine Learning Algorithms** (Naive Bayes, SVM, KNN, Decision Tree, Gradient Boosting, XGBoost, CATBoost, Generic Algorithms) [122]
- **Reinforcement Learning (RL)** (Q-Learning, Deep-Q-Learning, Federated Learning, Machine Common Sense, Learning with Reduced Labelling, OpenAI Gym) [42, 119, 122, 123, 124]
- **Quaternion Valued Neural Network** [119, 125]

Fundamentally, AI progress aims to expand its mathematical, computational, conceptual, and algorithmic underpinnings. Advancements are driven by a reduced need for data, enhanced agility, increased resilience, improved problem-solving, and generalisation of scenarios while synergistically cooperating with human elements or *"wetware"* (i.e., biological) systems.

Advanced Algorithms (AA) is analysed along two dimensions: learning architectures and developments in AI fundamentals. However, AI's natural limitations and drawbacks heavily constrain both dimensions (see Figure A.3). Nonetheless, they attempt to address intrinsic issues such as problem set optimisation, transparency, and trust while facing brittleness and generalisation issues. Overcoming these challenges will increase military decision-making effectiveness and efficiency through symbolic, and sub-symbolic approaches [126], neural networks, and learning architectures.

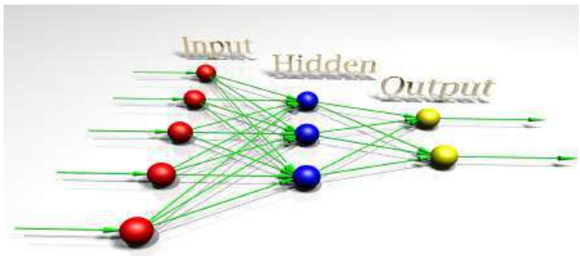


Figure A.4: *Artificial Neural Network - AI Methods (CREDIT: WikiCommons)*

On the other hand, AA methods are evolving towards next-generation AI methods that build on biological modelling and mimic human cognitive functions. Examples of such approaches are:

- Long short-term memory neural networks [119, 121, 127];
- Hierarchical recurrent neural networks [119, 121];
- Residual neural networks [119, 128];
- Convolutional neural networks [118] (with significant research interest on convolutional autoencoders [117], and dilated convolutional neural networks [119]); and
- Quaternion-valued [119, 125].

The above AA is integrated within Learning architectures, making AI more agile and resilient while using fewer data [42, 129]. Different methods such as Deep-Q learning [119, 122], federated learning [123, 130], and *"machine common sense"* [42, 124] are promising research areas, though antagonist strategies involving generative adversarial networks (GAN) [119, 120]. Siamese networks [119, 131] have proven themselves especially powerful.

AI Application

The application of AI is considered a priority S&T investment area and is currently being driven by industry [86, 132]. On the one hand, advancements in the application of AI in the public domain have been significantly enabled by the production and availability of open-source tools and data (e.g. Enron dataset [133]). On the other hand, military AI applications are usually limited to context. They lack specific datasets for training algorithms, though Alliance nations are still investing and progressing on AI applications [107, 134]. AI continues to be embedded within many systems, processes, and defence capabilities. Some of the more exciting and potentially disruptive applications are presented below [107, 134, 135]:

Figure A.5: *Can AI be an inventor?*

- **Decision making** [136, 137, 138, 139, 140]
- **Cybersecurity**
- **Automated Vehicles** [135]
- **Artificial Social Intelligence**
- **Cognitive Warfare** [141]
- **Automating Disinformation**
- **Geospatial AI**
- **High-Resolution Image Recognition**
- **Semiconductor Design**
- **Generation and Identification of Deep-fakes**
- **Data-Driven Behaviour Modelling**
- **Dynamic Airspace Control**
- **Scientific and Technological Discovery**
- **Text to Image Synthesis**
- **Human Terrain Navigation**

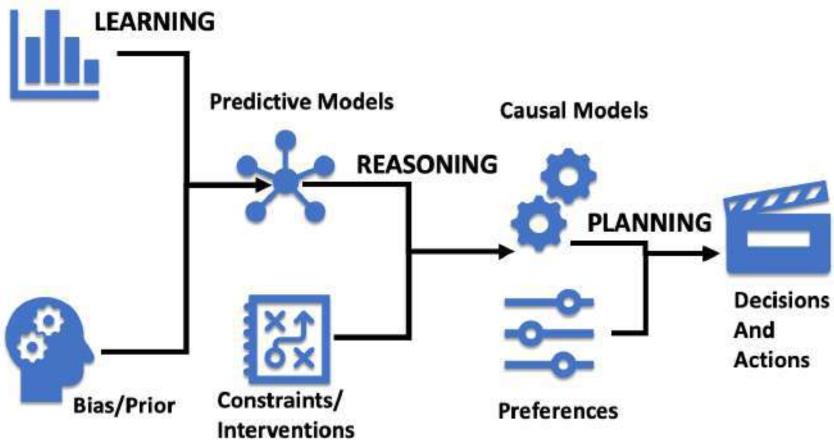


Figure A.6: *AI and Decision Making CREDIT:[140]*

The extent to which AI enables society and scientific domains is still being determined. However, AI's unique ability to unlock or act as an enabler of new capabilities and scientific discoveries across multiple disciplines (e.g. scientific, mathematical and engineering, educational [142], medical [143, 144], and others) contribute to its comparison to other past revolutionary technologies such as electricity [103].

The National Security Commission on Artificial Intelligence (NSCAI) contextualised AI *"as the engine of invention"* [103] and proposed some examples (Figure A.7), which have been complemented in the sections below. Instances of the impactful nature of AI span from NLP, evolve into more humanised NLU (e.g. language translation) and continue towards AI-enhanced modelling and simulation based on integrated multi-modal cloud infrastructures (e.g. transforming crises responses). Alternatively, combined with autonomous technologies such as drones, AI can empower first respondent forces by augmenting their ability to orient themselves and map out unknown surroundings. Lastly, among other examples, AI contributes to operational and strategic thinking and planning while accelerating C2 and sharpening logistics.

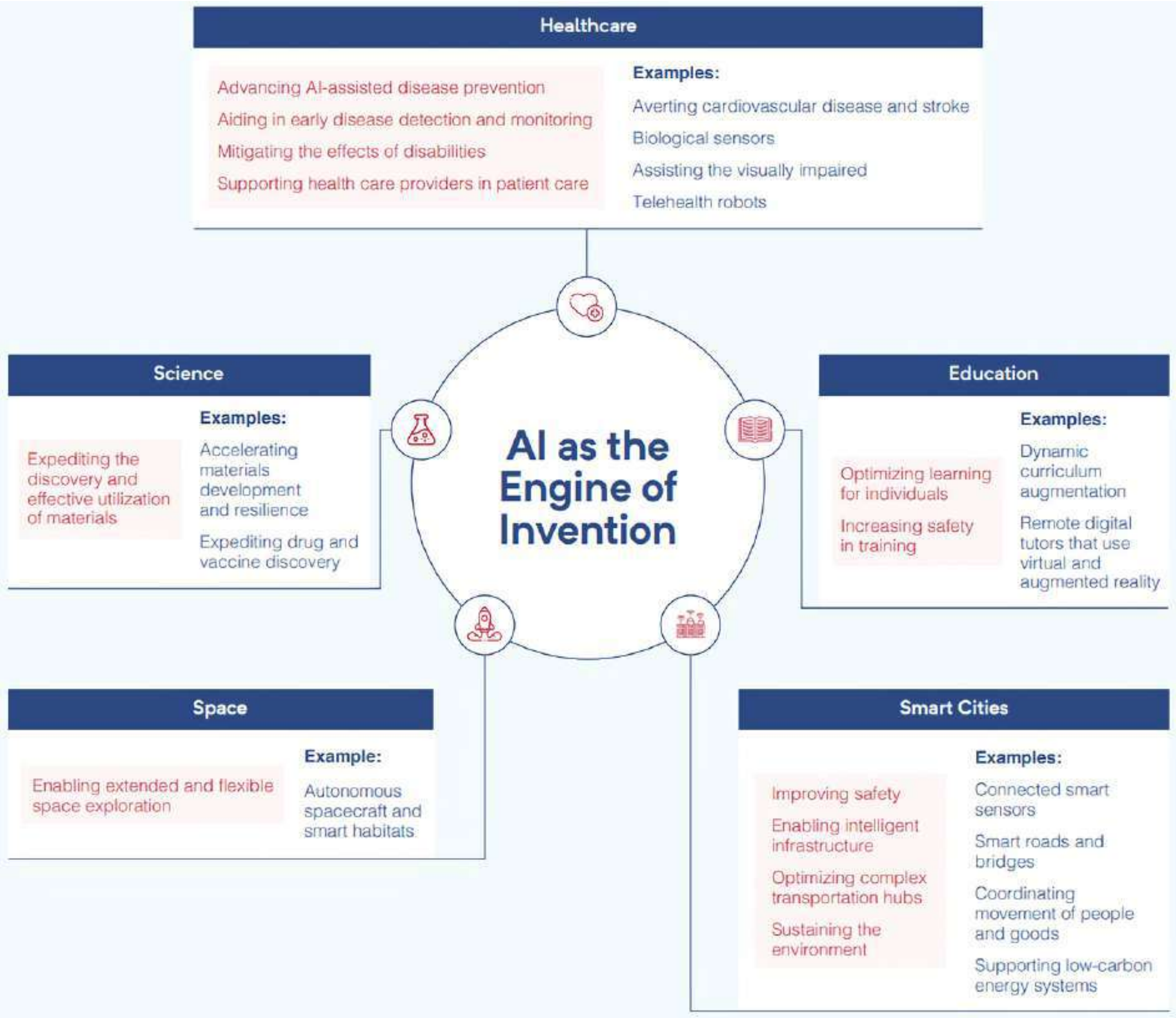


Figure A.7: *AI as the Engine of Invention (CREDIT: [103]).*

AA methods such as ML and DL contribute to increasingly diverse data-driven **decision-making** and intelligence analysis application [145]. In particular, AI-enhanced human decision-making is used for large data collection from multiple sources, and anomaly detection within a system [135].

The speed of decision-making processes (e.g. the observe-orient-decide-act (OODA) loop) provides critical leverage to gain an advantage, and decision-making superiority over adversaries [145, 103].

The extended use of AI-enabled techniques exposes and empowers **cybersecurity**. AA, automated and autonomous systems paired with human expert systems enable a predictive model of cyber-attacks and support identifying and patching vulnerabilities; or detecting and defending against threats [135, 145].

Some of these threats include using AI-enabled systems in the context of **Cognitive warfare**. Indeed, cyber hacking, technological espionage, blackmail, and illicit technology transfer [103] are used as means of **hybrid warfare** and **mis-/dis-information** techniques [103, 145, 146, 147, 148]. The previous threats highlight the potential role of AI/ML regarding improvements in deception and information operations, automating disinformation, and in the generation and identification of deep-fakes, especially in the civil and political domains [103, 145, 146, 147, 148, 149].

Figure A.8: *AI Cyber operations*

AI techniques may be used to digest large datasets of textual data to conduct sentiment and social media analysis. Unsurprisingly, such large data collection exercises can be leveraged politically and militarily to influence storytelling, narrative creation and present emerging threats to politics [145, 146]. Some AI techniques, such as behavioural research advances in natural language processing (NLP) and AI-enabled synthetic text, video and audio (e.g. fake social media posts) in autonomous agents (e.g. bots) use disruptive deep-fake information as a statecraft tool to shape public perception to convenient geopolitical or military significant storytelling. Hence, demonstrating how content-based AI-enabled information is weaponised and presents a threat [145, 146, 149].

Further applications of embedded AI in **autonomous vehicles (AVs)** provide the intelligence behind the decision-making process, planning and execution of tasks [135]. For instance, vehicle control and human assistance depend on the level of entrusted autonomy. Standard or partial AVs perceive the context relying on advanced sensor networks and interact within it, signalling the need for human intervention. Whereas, **highly automated vehicles (HAVs)** depend on AI to operate complex data-intensive decision-making functions required to understand the surroundings, plan for subsequent actions, and manoeuvre [135]. For instance, Project Maven embodies and weaponises the convergence of AI algorithms and drones in support of mission intervention [134].

Figure A.9: *Embedded-AI in Autonomous Vehicles*

AI's ability to perceive and interact within an environment comes from advances in computer science, sensors and geospatial technologies, human-logic or interpretations, and AI techniques. For example, all improving performance of deep neural networks (DNNs) algorithms used to recognise and train on selected images, objects detection, faces identification, NLP)/(NLU), translation, and so forth [135].

Drawing upon DNNs advancements, NLP has reached human-level performance with NLU. This evolution contributes to the next step of **text to image synthesis**, which consists of systems that can generate images based on textual data. Generative AI is considered one of the most challenging areas of AI [145]. In addition, breakthroughs in **high-resolution image recognition**, spanning from facial recognition to more subtle facial expression, enable biometric identification through facial features and emotion analysis [145]. Furthermore, use cases in the medical domain point out AI's high-resolution image recognition capabilities, which allow it to identify tumours and cancer cells [143, 150]. Thereon, raising expectations for military or counter-terrorism applications [145].

Human-Machine Symbiosis

Proficient human-AI teaming is a cornerstone for future AI applications. Mastering the harmonisation of AI with human-driven systems to create an effective psycho-social-technical collaborative system will be a game changer.

Figure A.10: *Human-Machine Symbiosis*

Research on human-machine synergies is moving forward rapidly, focused on developing explainable an observable AI, understanding trust-building and trustworthiness, entrusted authority, and ensuring confidence (validation and assurance) in the operationalisation of AI-enabled systems [151, 152, 103].

Increasing scientific understanding of the human mind will accelerate human-machine interfaces as a pervasive disruptor. Complementary, **advanced NLP** progress on language processing and Learning enables system development to process complex inputs and engage in human-like conversation while developing a collaborative intelligence among cohorts of agents. Still, **XAI**, **trust**, and **testing, validation, verification & assurance (TVVA)** remain critical challenges for AI in human-machine symbiosis as for any defence and security environment.

Explainability of AI intrinsically relates to **trust**, which is the Achilles heel of **human-machine teaming**. Understanding how to generate a trusted relationship between humans and AI and what it means for AI to trust human judgement [42, 153] represents a difficult technical and psychological challenge. Central to building trust is understanding (at some level) and explaining how an algorithm made a particular assessment and considered it in making this decision. New ML techniques are being developed to support their assessments and explicitly communicate associated constraints and limitations.

Other groundbreaking approaches are being explored to improve human interaction with AI. The objective is to develop user-friendly interfaces capable of surfacing acquired knowledge on demand. These human-interpretable ML models are combined with visualisation and communication interfaces more conducive to human understanding, and evaluation [42, 106, 153, 154, 155].

TVVA also represents a critical aspect of trust, ultimately one of the most challenging aspects of the operationalisation of AI/ML. R&D is moving forward to create systems engineering methods, standards, assessment tools and software; to ensure that deployed AI is timely, affordable, trusted and fully mission capable. This will require real-time tools to guarantee reliability and traceability. In addition, research into new continuous learning algorithms requires that agility be balanced with the need for mission accreditation [42, 153].

Research is also focused on manipulating human decision-making by AI [156, 157].

Resilience

Since AI is being adopted and deployed by both BLUE and RED forces, AI-on-AI engagements are currently emerging (mainly in the realm of disinformation). As a result, the resilience of intelligent systems and counter-AI activities become increasingly critical to detect, deflect and limit the impact of attacks on Alliance AI while undermining adversarial AI-enabled systems, as noted by the NATO Chief Scientist's research report (CSRR) on AI [1].

Adversarial use of AI/ML unveils a collection of tools and techniques designed to defeat or obstruct intelligent systems currently impacting military sensors, weapon systems, and decision support systems (e.g. Intel, Socint). The interference with, and jamming of, inputs modifies outputs imperceptibly to the human eye, thereby interfering with daily and future operations [158]. In contrast, tightly dependent on thorough intelligence on adversary systems [159, 160, 161]. Potential uses of **advanced ML** in research are identified as: **(i)** countermeasures against detectors in next-generation sensor systems; **(ii)** obstruction of ML-based remote sensing data analysis.

The importance of exploring AI countermeasures is largely shared among the S&T and military community as it represents a technology prime for increased R&D. As Alliance and competitor forces progressively use AI, **AI countermeasures** become increasingly critical to explore to understand how to protect and exploit AI-based systems [159, 160, 161]. Like any operational domain, there is a need

[1]To access the report visit <www.sto.nato.int> - Publications, NATO Chief Scientist's Reports section

to detect, deflect and limit the impact of attacks on Alliance AI. **AI robustness** set of tools developed for TVVA and those used to create adversarial AI countermeasures are being extended into a real-time defence of BLUE-AI systems, including the need to harden AI against deception by adversaries.

Figure A.11: *Countering AI Systems*

Certainly, **counter-AI** in general, **countering adversary AI** and associated decision processes through AI manipulation and deception is a difficult technical challenge yet to be solved. Similarly, detecting AI manipulation is not straightforward. On the contrary, AI-on-AI conflict is not just a possibility but is a complex, evolving reality in cognitive warfare and disinformation [149]. Therefore, AI systems engagements will become increasingly common, thus requiring thorough identification of adversarial AI, model AI responses, timely and efficient weaknesses assessments, and counter-AI strategies development [162].

Military Implications

Artificial Intelligence is currently transforming warfare. According to NSCAI 2021, [103]:

> *"AI applications are transforming existing threats, creating new classes of threats, and further emboldening state and non-state adversaries to exploit vulnerabilities in our open society. AI systems will extend the range and reach of adversaries [...] just as the missile age and terrorism bring threats closer to home. Because of AI, adversaries can act with micro-precision but at a macro-scale and with greater speed. They will use AI to enhance cyber attacks and digital disinformation campaigns and to target individuals in new ways. AI will also help create precisely engineered biological agents. And adversaries will manipulate the AI systems we will rely upon."*

Blue's comparative edge depends on surgical leverage, exploitation and adoption of AI. Besides, the resulting AI capability will underpin the Alliance's ability to compete, deter, and win across domains [163].

BLUE

AI will significantly impact Alliance military capabilities and forces. This impact will predominately occur through China's new concept of intelligentized warfare and the control of the enemy's will [164]; embedded AI in other associated technologies such as virtual/augmented reality; quantum computing; autonomy; modelling & simulation; space; materials research; manufacturing & logistics; and big data analytics [108].

In addition, AI will transform nuclear, aerospace, cyber, materials and biotechnology. Some argue that these effects will have a strategic impact on the same scale as the introduction of atomic weapons [165]. Furthermore, an over-reliance on AI systems will introduce significant new vulnerabilities and usher in an adversarial AI arms race [103]. Figure A.12 offers a summary of emerging AI threats BLUE should consider while adopting, implementing or fielding any AI solution.

Even though AI presents risks, potential defence applications should continue considering the appropriate level of human control and accountability. Nevertheless, many of these scientific and technological developments will inevitably impact operational, strategic and enterprise capabilities/business functions.

Enable

- **Enterprise Management:** NATO requires more efficient and effective processes for enterprise resource management (investment and business planning, program performance and risk management, strategic transformation and improvement initiatives, strategic readiness management, and strategic management practice). These improved processes will be based on advanced analytics, and

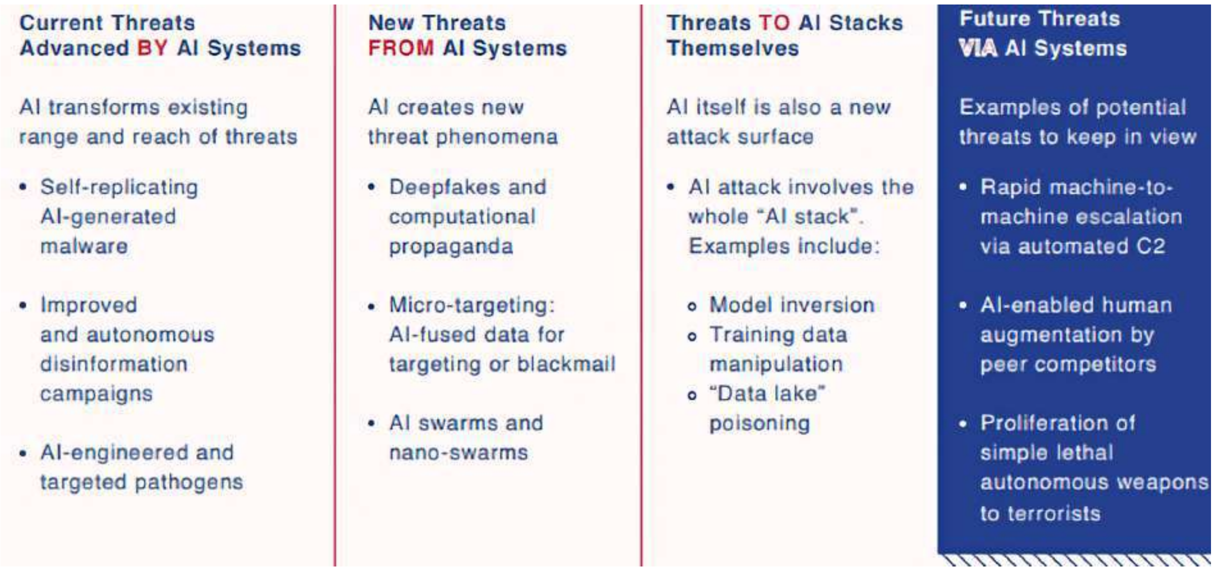


Figure A.12: *Emerging threats in the AI era: How AI is transforming the threat landscape (adapted from [103]).*

evidence-based decision-making [166]. AI can assist in cost analysis, assessing economic impacts and drivers, and providing timely, evidence-based decision support for finance.

- **Applied AI/Logistics:** The support of AI technologies could increase the speed and responsiveness of logistics planning in future operations.

- **Symbiotic human-machine integration:** through meaningful human control represents a must to have to extract value from technologies such as AI, big data analysis, and the application of autonomy, which can enable NATO to operate efficiently and respond dynamically to changing circumstances, supporting the effective execution of operations at all times and in all places.

- **Decision-making:** The more intelligent and autonomous systems exceed human abilities, the faster they are adopted in complex decision-making processes and self-directed activity. This will result in competition between battle networks, each seeking a combination of effects that will lead to a decisive victory [145].

Prepare

- **Advanced Algorithms:** With clear synergies with other technologies, these will benefit processing data and predicting future events.

- **Human augmentation:** AI paired with technologies such as augmented and virtual reality and biotechnologies can increase the effectiveness of personnel and provide environments for continuous Learning and development. Furthermore, all such technologies can assist in establishing, preparing, and sustaining a sufficient and effective presence at the right time, keeping the flexibility necessary to adapt to possible changes in the strategic environment.

- **Training**: AI systems (especially when paired with virtual/augmented reality systems) can improve individual and customised training through real-time adaption to human behaviour and generate bespoke training environments or scenarios.

- **Capability Planning**: AI will support the development of analytical solutions to assist in long-term planning within NATO, including supporting complex decision-making that cuts across traditional internal boundaries; assisting assessments of complex factors and effects chains for decision-makers.

Project

The Alliance's ability to respond dynamically to situations in different operational domains, deliver forces whenever and wherever required, and maintain effectiveness in the face of opposing-RED technological systems is largely affected by AI and spans across EDTs. All such technologies will contribute directly to achieving mission goals within NATO's core tasks of defence and deterrence, crisis management, and cooperative security.

Engage

This subsection emphasises operational effects to promote technologies such as novel materials, innovations in sensing, and the application of autonomy that can enable NATO forces to respond to more dynamic situations in different operational domains, deliver effect whenever and wherever required, and maintain effectiveness in the face of opposing technological systems. Moreover, all such technologies can contribute directly to achieving mission goals within collective defence, crisis management, and cooperative security.

- **Weapons and Effects**: AI is seen to be of potential use in cross-cueing, trajectory planning, collision avoidance, swarming, weapon selection, battle damage assessment and effects coordination.

- **Unmanned Vehicles (UxV)**: Areas of potential AI impact in trajectory planning, collision avoidance/swarming, operator assistance (e.g. one operator controlling multiple-UxVs). Dynamic mission planning for autonomous systems (e.g. navigation, data collection, environmental characterisation and adaptive sensing). Integrating deep learning systems into mobile platforms will enhance robotic capabilities for navigation within dull, dangerous, dirty or dire situations. AI could enable fully autonomous explosive ordnance disposal in urban areas. Intelligent autonomy will enable capabilities such as long-duration unmanned underwater vehicles.

Protect

- **AI Countermeasures:** AI systems are vulnerable to adversarial attacks throughout their life cycle. Since the use of open-source pre-trained models carrying hidden backdoors, or the selection of polluted/poisoned datasets to train the model. Consequently, the algorithm can be subject to misinformation and physical manipulation (e.g. specific camouflage, unknown behaviour, unexpected objects, and hidden agenda). Thus, exposing AI to cyber attacks since the earliest phases of its development. Countermeasures in defence of BLUE's AI-enabled capabilities involve technologies such as directed energy, signature reduction technologies and novel materials, which can enhance the ability to locate accurately, classify and neutralise threats across all domains and remotely inform the warfighter of the details of a particular threat. All such technologies contribute to minimising the vulnerabilities of personnel, facilities, material, and activities to any threat and in all situations. RED can introduce their own AI during peacetime into the Hybrid War, stressing the need for counter-RED use of AI not only during a crisis. Hence, the emphasis on threat detection and countermeasures technologies will enhance the interception and mitigation of threats from various capabilities. For instance,

- **CBRN**: NATO requires a suite of enabling and integrated technologies that provides rapid detection, identification, and monitoring (DIM) of CBRN threats/hazards during any mission in all operational domains, which informs on the course of action necessary to mitigate the threat/hazard. AI may support improved autonomy to perform detection, sensor integration and data fusion. AI is seen as a means of alleviating the burden of human involvement in determining the position of sensors and initiating data fusion and interpretation. In addition, AI will enhance command situational awareness and support through new abilities to self-organise and assume the optimal posture needed to achieve desired end-states. Ultimately, this will increase the knowledge of current and potential controlled agents incorporated in software suites in Stand-off platforms, increasing hazard management capability.

- **Tamper-proof and resilient systems:** Ensuring a secure information processing chain against information manipulation that might occur at any level.

Sustain

This subsection emphasises rapid response and recovery to promote technologies that can enhance the efficiency and sustainability of the armed forces both in the systems they use and in human adaptiveness and recovery. Technologies such as biotechnologies, autonomous enhancements, and AI solutions can serve a range of purposes that contribute to response and recovery from effective diagnosis, improved information sharing, and enhanced self-sustainment of units in theatre. All such technologies enhance the capabilities to plan and execute the timely support and sustainment of forces.

- **Logistics**: AI systems (especially when paired with digital twins) have the potential to minimise equipment downtime, minimise system failures, improve inventory and repairs management etc. Problems of these sorts are similar to those encountered in the commercial world and are therefore primed for early adoption by NATO.
- **Medical**: Modern military forces require clinically relevant and empirically validated medical interventions and associated procedures. AI has the potential to assist in developing evidence-based clinical knowledge, evidence-based diagnostics and treatment best practices to reduce morbidity and mortality and maintain/recover essential functions in the face of hazards from across the mission spectrum. Further, AI will provide automated decision support and diagnostic support tools to assist medics in the field who are dealing with novel trauma situations.

Inform

The subsection emphasises enhanced situational awareness to promote technological solutions such as AI, Blockchain applications, and data fusion and exploitation, which can reduce information-sharing times, strengthen the survivability of ISR systems, and increase trust in situational awareness. All such technologies seek to inform the warfighter better, providing the knowledge required to allow commanders at all levels to make timely and informed decisions.

- **C4ISR**: War-fighting units will employ trusted AI-enabled autonomous systems capable of performing tasks that move beyond those deemed dull, dirty, dangerous or dear. Some of the areas for potential application are expected to be in the increased use of virtual assistants (analogous to *Google Home*, *Apple Siri*, or *Amazon Alexa*), AI-enabled decision support to war games and AI recommended courses of action (COA). AI is a good foundation for enhanced data fusion, categorisation, and effects-based assessments (or targeting). For example, Intelligence analysts can leverage trusted systems capable of tasking, collecting, processing, exploiting, disseminating (TCPED), and retrieving information across the spectrum of available sensors and relevant archival data. Additional areas of AI integration will include enhanced indications & warnings, information and knowledge management tools, and decision aides, enabling more rigorous and robust intelligence analyses. This will include establishing patterns of life, human terrain mapping, social network analysis, and decision support for targeting. Very high-speed, very low-power neuromorphic electronic components offer the possibility of autonomous systems and computer architectures that may rival human perception at very low power, enabling embedded sensor processing for scene recognition, target discrimination, and identification.
- **Tamper-proof and resilient systems:** Ensuring a secure information processing chain against information manipulation that might occur at any level. Ensuring supply chain (and development environment for systems and sub-components).

C3

In support of consult, command and control (C3), AI contributes to a *decision advantage*, promotes and enables technologies that can improve decision quality, shorten the decision cycle, and increase information superiority over opponents. For instance, blockchain applications, AI, machine learning, and data fusion can assist staff in correlating data streams and communicating across widely distributed and highly mobile forces. At the same time, increasing coordination opportunities between different command levels and functional areas. All such technologies improve the capability of commanders to exercise authority over and direct the full spectrum of assigned and attached forces in accomplishing the mission.

RED

The benefits of RED are similarly applicable to those available to BLUE forces. However, reliance on AI will also increase the potential impact of cyber and information attacks. Further, with fewer ethical and legal bounds, RED may enable AI functions along the whole kill chain to achieve tactical decision advantage or as a response to a loss of communications.

The NSCAI 2021 has plotted emerging AI threats, specifically and among others:

- **Cyber**: AI systems are particularly vulnerable to cyber attacks, whereby small, deliberate changes may lead to erroneous recommendations or sub-optimal actions.
- **Information**: Advances in speech processing and synthesis technology will likely allow the realistic simulation of friendly and enemy personnel over communications links and broadcast media (e.g. deep fakes). Combined with twitter-bots and other social media hacks, ever more effective AI (e.g. generative adversarial networks (GANs)) will greatly increase the scale and effectiveness of hybrid attacks, whether by near-peer or asymmetric threats, [167].
- **Aberrant behaviour**: Unanticipated behaviour in AI systems is simultaneously a strength (e.g. creating entirely new strategies [168] and, at the same time, a significant potential liability. Limitations imposed through legal, ethical and policy considerations may be more relaxed for peer or near-peer opponents. RED weapon systems unrestricted by the physical limitations of the human body, whose behaviour is often unpredictable and inexplicable, would constitute a formidable adversary.
- **Improvised Explosive Devices (IEDs)**: Increasingly intelligent learning systems will enable new generations of improvised explosive devices, less susceptible to traditional countermeasures.
- **Neuromorphic AI**: Bio-brain models, interfaces and neuromorphic chips will enable RED and BLUE's path toward General AI [169], with attendant concerns about the long-term implications.

Interoperability

AI interoperability presents a major challenge. As autonomous systems proliferate, there will be an increasing need to interoperate, share data information and establish specialised communication much like humans must. Moreover, in a NATO context, autonomous systems and their human controllers must act together coherently, effectively and efficiently to achieve Allied tactical, operational and strategic objectives.

In such an interoperable system, interfaces will need to be understood, and heterogeneous systems, present or future, will need to work together with no or few restrictions. Therefore, common and standardised procedures must be established by NATO to define and conduct verification, validation and accreditation (VV&A) of AI-enabled operational decision support AI systems before they are used in Alliance military operations and all AI systems at large. Organisations will harness the full potential of interoperable and interconnected AI systems in the first instance through process building and policy writing on differing VV&A [104]. Secondly, addressing the limitations and pitfalls around AI-Black box and explainability [170, 42] and, simultaneously, investing heavily in M-M teaming and symbiosis, thus increasing trust across all components at all levels of the organisation.

S&T Development

AI continues to demonstrate incredible capabilities at expanding and enabling S&T. Potential and challenging disruptive applications to revolve around a more socio-political perspective of AI, the cognitive dimension of warfare, and the automation of malicious use of AI (e.g. automating disinformation).

The cornerstone of any future development is Human-AI symbiosis and the ability to enable human-like collaborative (trusted) systems at both psychological, social and technical levels. Further research is needed on AI-on-AI engagement as BLUE and RED forces increasingly adopt AI-enabled solutions. Potentially impacting NATO's ability to detect, deflect and limit an attack's impact on BLUE-AI.

State of Development

Data

BDAA and AI are expected to be increasingly prominent. Their synergies enable intelligence and advanced Analysis at a super-human level (building on Quantum synergies). Considering the growing complexity and vast volume of data available in an even wider net of heterogeneous sensors, the need for AI-advanced algorithms to extract value and actionable insights it's more important than ever.

RAS

AI will be increasingly embedded in **Warfare Platforms** and weapons systems across the domains of operation (land, maritime, air, space and cyber).

Space

See Appendix J.

Hypersonics

Hypersonics and AI synergies are expected in the next 20 years. Yet, the conceptualisation is still in the theoretical domain. Even though some Hyper-AI instances could lead to weak signalling of an upcoming turn, the synergy is still far from actual trends.

Quantum

Quantum Computing may enable AI to process larger data volumes efficiently, identify complex patterns better than traditional AI, and improve all performance. . The rise of Quantum AI will strengthen and harden NATO's technological systems, enhancing security, communication and resilience.

BHET

AI-Biotech applications largely concern biological processes, fastened drug development, logistic and supply chains, industry data management, early diseases identification and others. Nevertheless, although AI positively impacts biotechnology, NATO shall remain vigilant. Emerging breakthroughs of AI into biosensor design and synthesising unknown and novel bioweapons, chemicals and elements will increase CBRN-E threats and hazards and enhance drugs, antibiotics and medicine at large[171, 172].

Materials

Like Biotechnology, AI enables other science fields to discover new materials, elements and molecules. Those will be used for diverse applications and possibly in combination or unlock further EDTs potential. For instance, future batteries, semiconductors, green grid, next generation of computing and communication, advanced 3D-printing and nanotechnologies.

Energy

Since digitalisation, AI/ML is shaping future energy systems. For instance, powered or smart grids are nets that transport both data and electricity.

E&EM

AI optimises Semiconductor Design and Electronic Design Automation tools (EDA). For instance, chip semiconductor packaging was a low-value element of the semiconductor design process for years. However, advanced packaging techniques enable sophisticated new chip designs using 3D stacking, heterogeneous integration, and modular chiplets to create more complex and sophisticated semiconductors.

STO Activities

Several STO Scientific and Technical Committees have produced significant research on *Data* technologies. Many panels have ongoing activities on several topics aligned with these technologies. The following is a sample of ongoing activities:

- AVT-331: Goal-driven, multi-fidelity approaches for military vehicle system-level design
- AVT-368: Data fusion and assimilation for scientific sensing and computing
- AVT-ST-009: Technical Support to NATO Next Generation Rotorcraft Capability (NGRC)
- HFM-281: Personalised Medicine in Mental Health and Performance
- HFM-294: Big Data In The Military: Integrating Genomics into the Pipeline of Standard-care Testing & Treatment
- HFM-311: Cognitive Neuroenhancement: Techniques and Technology
- HFM-316: Expert panel for state of the art cardiovascular risk assessment in aircrew and other high-risk occupations.
- HFM-330: Human Systems Integration for Meaningful Human Control over AI-based systems
- HFM-IST-366: Stakeholder involvement methods for Ethical Legal and Societal Aspects of Military AI
- HFM-SET-353: Operational CBR Threat Situational Awareness
- IST-169 (AI2S): Robustness and Accountability in Machine Learning Systems
- IST-200: International Conference on Military Communication and Information Systems (ICMCIS)
- MSG-186: Multi-Dimensional Data Farming
- MSG-205: Allied Interoperability and Standardization Initiatives for Digital Twins
- MSG-213: M&S in support of Building Resilience and Refugee Flow Management
- SAS-143: Agile, Multi-Domain C2 of Socio-Technical Organizations in Complex Endeavors
- SAS-157: Automation in the Intelligence Cycle
- SAS-158: Employing AI to Federate Sensors in Joint Settings
- SAS-159: How could Technology Development Transform the Future Operational Environment
- SAS-160: Ethical, legal and moral (ELM) impacts of novel technologies on NATO's operational advantage – the "ELM Tree"
- SAS-167: Assessing the value of cyber operations in military operations
- SAS-168: Coalition Sustainment Interoperability Study
- SAS-181: Exploiting Reinforcement Learning to Achieve Decision Advantage
- SAS-IST-179: Semantic Representation to Enhance Exploitation of Military Lessons Learned
- SCI-326: Electronic Support (ES) Techniques Enabling Cognitive Electronic Warfare (EW)
- SCI-354: Air Platform Generic Self-Defence
- SET-278: Machine Learning for Wide Area Surveillance
- SET-283: Advanced Machine Learning ATR using SAR/ISAR data
- SET-288: Integrating Compressive Sensing and Machine Learning Techniques for Radar Applications
- SET-302: Cognitive Radar
- SET-307: Advanced radar techniques for robust situation awareness and threat assessment considering Class I UAS in complex environments
- SET-310: Assessment of EO/IR Compressive Sensing and Computational Imaging Systems
- SET-311: 10th Military Sensing Symposium (MSS)
- SET-313: Advanced Methods for Hyperspectral Data Exploitation
- SET-315: Detection, Tracking, ID and Defeat of Small UAVs in Complex Environments
- SET-317: Multi-dimensional/Multi-platform Radar Imaging
- SET-318: AI/ML and Cognitive Radar
- SET-HFM-314: Multi-Omic Data Sciences Research Workshop
- IST-121-ET Behavior profiling in IoT
- IST-122-ET Designing resilient autonomous vehicles
- IST-123-ET Exploring Countermeasures against Misinformation of a Nation's Population
- IST-124-ET Using an AI Maturity Model to Accelerate Successful AI adoption
- IST-ET-125 Evolving Threat Landscape for Coalition AI/ML Systems
- IST-194 Adaptive Networks at the Tactical Edge
- IST-192 ANTICIPE*@STJU-22

Scientometric Analysis

Keywords associated with AI as derived from STEAM analysis are shown in Figure A.13.

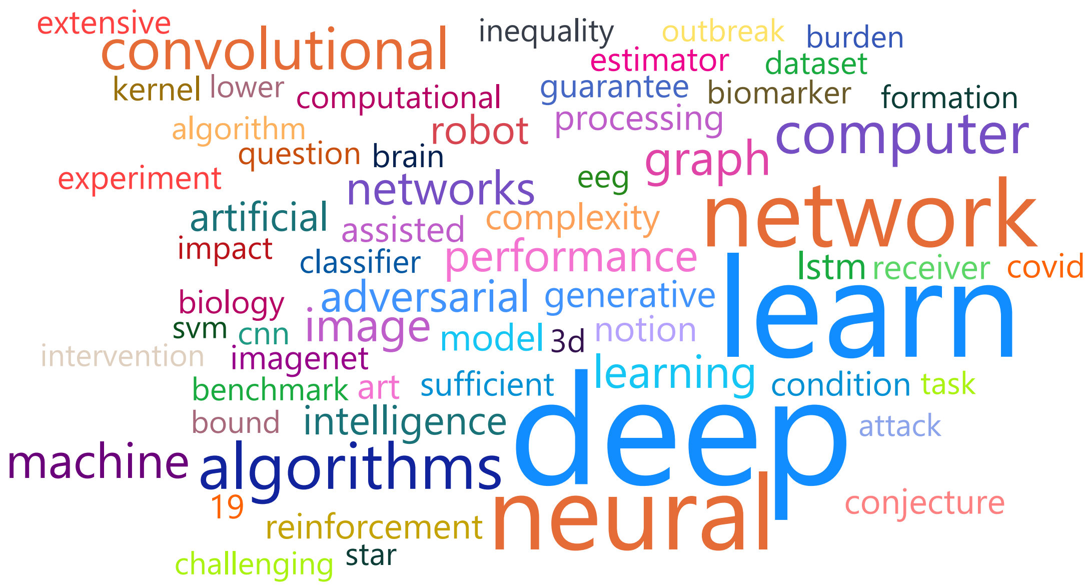


Figure A.13: STEAM - Artificial Intelligence - Keywords

Survey Results

The following table presents the assessed potential impact, state and rate of development and identifies areas for focused research.

Table A.1: Artificial Intelligence (AI) 2023 - 2043.

EDT	Technology Focus Areas	Impact	TRL	Horizon
AI	Advanced AI	Revolutionary	3-4	2035 or (+)
	Applications	High	5-6	2025-2030
	Counter AI	Revolutionary	3-4	2030-2035
	Human-Machine Symbiosis	Revolutionary	3-4	2035 or (+)

Conjecture Card: AI

A. Detect/Generate Fake Media

Automatically detect or create fake media reports, video, audio and social media posts responsive to live situations or to communicate in real-time with targeted individuals or groups.

B. Virtual Command Advisor

Support and advise operational commanders in real-time with human-like reasoning and advice based on previous operations, leveraging comprehensive operational awareness.

C. Automated Communication

Equip individual soldiers to automatically, instantly and accurately translate languages, body language and human emotions anytime and anywhere.

D. Spoof AI Systems

Covertly get inside the OODA loop of adversary's AI systems to insert misleading data or information to impact their decision-making processes.

E. Deep Fakes

Modify and mimic adversarial communications, including those in real-time (video, audio, etc.) to destroy trust.

F. Optimise Vehicle Use

Optimally allocate and route vehicles (e.g. transport, medevac, ISR, tanks, APC, etc.) using real-time situational awareness of the operating environment.

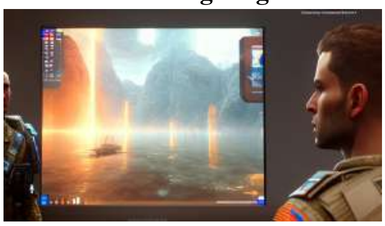
G. Disruptive Behaviour

Accurately predict the behaviour of humans or groups from background data (e.g. social media, surveillance, biometric devices).

H. Precision Engagement

Acquire and engage targets in a crowded, cluttered, dynamic environment with highly localised effects (kinetic or energy-based) and selective lethality.

I. Automated Targeting



Provide precision targeting advice across the military, economic, information, and diplomatic spectrum to achieve a desired operational/strategic effect.

J. Generalised AI

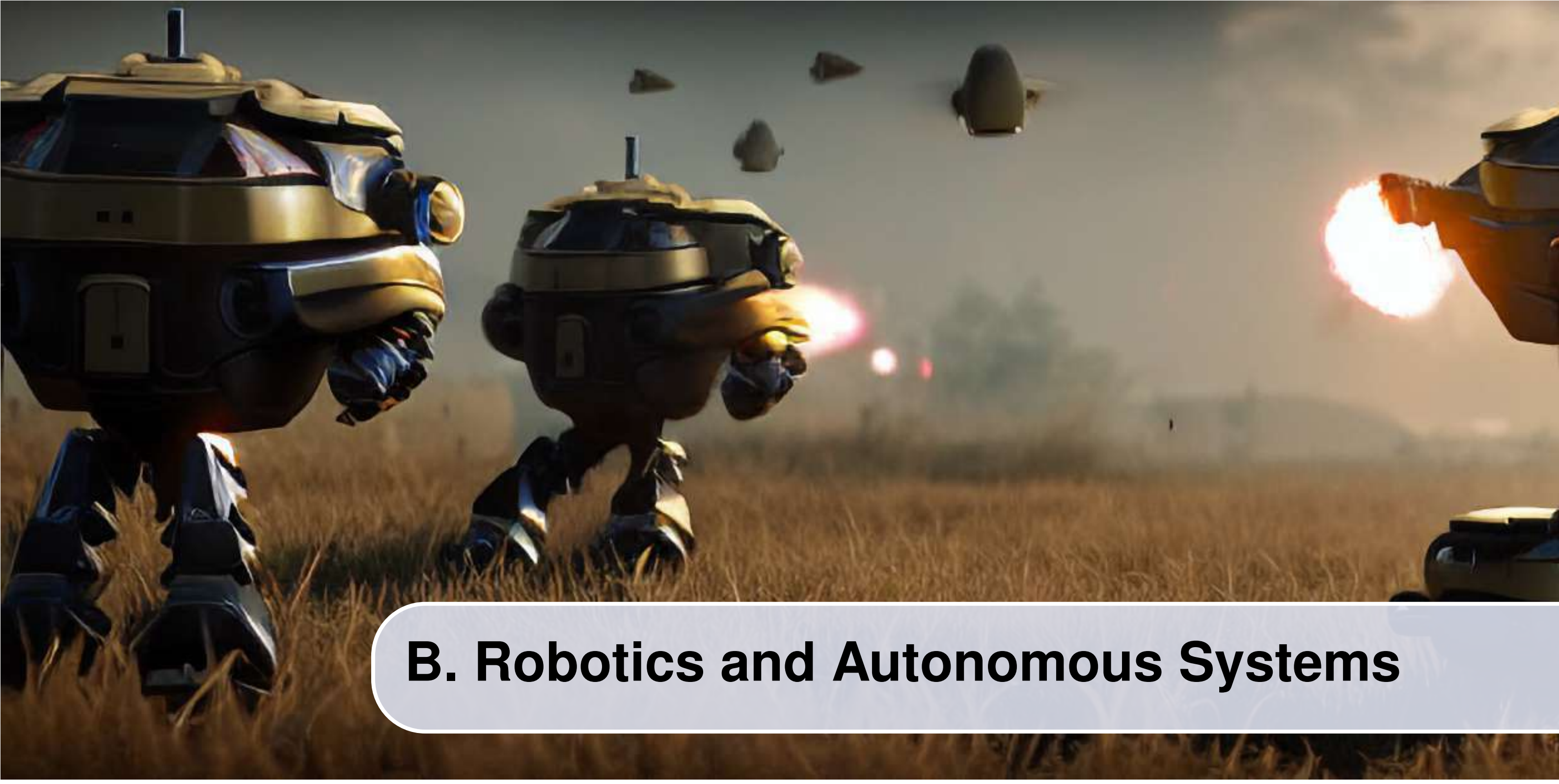
General AI has been achieved, with AI surpassing the capabilities of humanity.

K. Neurologically Fused

Integrated direct neurological linkages to allow natural human-AI interaction, collaboration and symbiosis.

L. Research and Development

Greatly improve the effectiveness and efficiency of R&D through AI-enabled exploration, meta-analysis, simulation and experimentation. AI are co-authors and may hold patents.



B. Robotics and Autonomous Systems

Autonomy

"Let's start with the three fundamental rules of robotics. . . . We have: one, a robot may not injure a human being, or, through inaction, allow a human being to come to harm. Two, a robot must obey the orders given it by human beings except where such orders would conflict with the First law. And three, a robot must protect its own existence as long as such protection does not conflict with the first or second laws." - *Isaac Asimov*

Definition

Robotics and Autonomous Systems (RAS, or *Autonomy*)

Autonomy is the ability of a system to respond to uncertain situations without human interference by independently composing and selecting different courses of action to accomplish goals based on acquired knowledge, a contextual understanding of the world itself, and assessment of the situation at hand [2]. As a result, it provides greater speed, agility, accuracy, persistence, reach and coordination, potentially reducing risks and costs. Thus, representing a system's ability to function, within parameters established by programming and without outside intervention, in accordance with desired goals, based on acquired knowledge and evolving situational awareness. [173]

Keywords

Autonomous Vehicles · Automated · U(A/U/CA/x)AV · Man-Machine Interface · Autonomy · Human-(in/out/on)-the-loop · Robotics and Autonomous Systems (RAS) · Human-Machine Teaming · Autonomous Anti-Submarine Warfare (A-ASW) · Autonomous Military System (AMS) ·

Developments

Overview

As NATO proceeds with its Autonomy Implementation Plan [174], autonomous systems are transforming and largely affecting Allies' security and defence postures. Autonomous Technologies (ATs) and Robotics & Autonomous Systems (RAS) are intrinsically related to AI, sharing many of the same strengths, weaknesses, opportunities, and threats. As well as momentum and inertia over technical and political debates, such as agreed definition; trust and explainability; Ethical, Moral and Legal (ELM) use of RAS and Autonomous Weapon Systems (AWS); and Lethal Automated Weapons Systems (LAWS).

Autonomous systems are a key element of the current and future battle space. They contribute to reducing risks and augmenting military capabilities, profoundly transforming the strategic calculus of modern warfare [175, 176, 177, 178]. Research demonstrates that RAS present a wide spectrum of short and longer-term opportunities acting as an Alliance capability and force multiplier across operational domains [174, 179, 180, 181]. Potential emerging and disruptive benefits regard scalability and cost reductions, variety and availability, miniaturisation breakthroughs, AI advancements and a deeper understanding of Human-Machine (H-M) and Machine-Machine (M-M) teaming, collaboration and symbiosis. Although, as covered by the Chief Scientist Research report on *Autonomous Technologies* [182], the ever-mature autonomous technologies adoption and deployment encompass various domains of operation, but yet significant S&T challenges (e.g. interoperability, system verification, and exploration of platform autonomy [183]) are to be solved and understood to master RAS capabilities fully and implement them ethically.

Therefore, Autonomy has become an important area for NATO military and security capabilities, and novel research underlining this area continues briskly. Over the next 20 years, four main areas of R&D activity are seen to be disruptive: **(1) Advanced RAS**; **(2) RAS Application**; **(3) RAS Man-Machine Teaming**; and, **(4) Counter-RAS and Resilience**.

Currently, there is no consensus around the definition of neither Autonomy nor RAS, and their interpretation is mainly context-driven. In this regard, the present document aims to provide overarching yet informed guidance but will not participate in the debate over the Autonomy and RAS definitions. For an in-depth comparative analysis, consult [184]. Therefore, there is a need to develop a clear distinction between automation and Autonomy in order to appreciate current developments and emerging trends. Autonomy speaks to the extent of self-directed behaviour, also called System Autonomy Entrusted (SAE) levels, ranging from fully manual to fully autonomous. In contrast, RAS sits in the autonomy spectrum with increasingly autonomous mechanical/kinetic systems [145, 185, 186, 187].

RAS and Autonomy enable each other. However, both capabilities depend on the intelligence and independence entrusted to the system executing specific tasks. On the one hand, the system automatically performs a defined set of specific functions is considered automated. On the other hand, automation assumes overarching human control and intervention to set requirements or conclude the task. This could also result in semi-autonomous systems if multiple sequences of functions are chained to the point where operators' inputs are not needed to execute tasks. Thus, enabling systems to run semi-autonomously.

On the other hand, Autonomy reflects systems' ability to perform pre-defined operations along a set course of actions without the operator's involvement. Those technological systems are called autonomous and are normally composed of complementary autonomous technologies as a system of systems. For example, Autonomous Vehicles (AV), such as driverless cars or trucks in the mining industry, and mobile robots in logistics. In other words, the circumstances or self-reliance to attain scattered tasking entrenched on systems' intrinsic situation awareness (integrated sensing, perceiving, analysing), planning and decision-making.

Therefore, Autonomy concerns an automation spectrum where (autonomous) intelligent decision-making is geared for unique missions, risk levels, and degree of human-machine symbiosis and teaming. However, given RAS's ability to explore a course of actions and establish the next moves while reducing human cognitive load, it remains challenging for autonomous systems to adapt to unstructured, unknown and uncertain circumstances dynamically [188, 189]. Mainly because of limitations in their ability to predict and infer actions from given inputs, thus reducing the foreseeable horizon.

Table B.1: *RAS Autonomy Continuum adapted from [190]*

SAE Level	Description	Capability	Control
0	No Automation	None	Human driver
1	Driver assistance	adaptive cruise control/lane keeping and parking assist	Human driver and vehicle
2	Partial automation	traffic jam assist	Vehicle
3	Conditional automation	full stop and go highway driving, Self parking	Vehicle
4	High automation	Automated driving	Vehicle
5	Full automation	Driverless vehicle operation	Vehicle

However, deployed unmanned weapon systems are remotely operated by a warfighter who augments the system's guidance, situational assessment, and decision-making - a supervisory role. These systems have demonstrated unquestioned value, playing vital roles such as Improvised Explosive Device (IED) interrogation, aerial surveillance, checkpoint inspection, and land or sea mine clearance. Although these systems help keep warfighters safe in 4D operational environments (Dull, Dirty, Dangerous and Dear) and have improved surveillance. Current unmanned system technology often increases manpower needs and cognitive load on today's warfighters. While some levels of Autonomy have been introduced in recent unmanned systems, the Autonomy lacks the intelligence to neither reduce manning requirements or the warfighter cognitive load; nor increase the pace of operations. Intelligent (advanced AI-enabled) Autonomy will enable capabilities that are not currently possible, such as long-duration crewless underwater vehicles operating in extreme and GNSS (Global Navigation Satellite System) denied environment [191, 192], where the vehicle must be able to work for months without human intervention or even communications. As well as crewless naval vessels capable of anti-submarine warfare (ASW), assisted communications through mobile radio transceivers, and subterranean operations [119, 153, 130, 193]

Table B.2: *NATO Autonomy developments area of interest.*

Developments area	**Use and Effects**
(1) Autonomous Systems [3]	- Autonomous hypersonic vehicles; - Bio-inspired micro and mini aerial vehicles; - Miniaturisation, small satellites (smallsats); - Hybrid-electric aero-propulsion systems; - Light-weight high-resolution hyper-spectral imaging technology for semi-persistent surveillance missions; - RF sensor miniaturisation; plasmonics for decreasing IR detector size; - Rapid 3D environment modelling; and - Use of robotic decoys
(2) Human-machine teaming	- Human performance enhancements; - Human-machine collaboration and communication;
(3) Counter-measures	- High power radio frequency (HPRF) weapons Mission Planning
(4) Autonomous Behaviour	- Control; - Swarm centric systems; and - Intelligent autonomy (i.e. increasingly advanced embedded AI)

Unmanned systems (or *autonomous* systems) are integral components in today's conflicts, as witnessed in Ukraine [178, 194, 195, 196, 197]. Drones (or *unmanned aerial vehicles (UAVs)* systems) and RAS are deployed for Intel collection and intelligent surveillance and reconnaissance (ISR), offensive strike missions, or general operations. However, RAS will further underpin operational success, as reduced costs, miniaturisation, broader employment, superior sensors, and sophisticated AI [175, 198, 199] will drive growth and more general usage. In particular, the growing importance of land and maritime Autonomy and the increased use of RAS for logistics, sustainment and manufacture is hard to overstate [200, 201]. Furthermore, future developments in multi-sensor fusion of increasingly sophisticated machines, computers, sensors and software will improve autonomous systems' accuracy and reliability while generating progressively intelligent systems capable of interacting with complex and unpredictable environments. Significant impact on NATO's physical and hybrid operational domains will be experienced as research advances on militarised sensors, advanced AI detection and tracking algorithms, and sensor planning for complex modelled and simulated scenarios. Likewise, data quality represents the cornerstone of development in sensing Autonomy, as autonomous systems are expected to rely heavily on unstructured geospatial and metadata.

Hence, RAS is a key enabler and beneficiary of developments in other EDT areas. Moreover, while fully autonomous systems may be a long-term goal, in the short and medium term, semi-autonomous systems will have more impact on operations. Therefore, from a technology watch perspective, developments of interest to NATO will be predominantly in the areas presented in Table B.2.

Advanced RAS

Adaptable RAS and learning-enabled autonomy are at the core of agile learning-based autonomy. Agile learning-based autonomy is an evolving technology and certification challenge. Advances in AI are driving RAS technical challenges, especially deep neural nets for perception, reinforcement learning for control and online model learning - see Appendix A. Work in this area is connected to the study of life-long Learning Machines [42, 153]. However, new systems engineering, formal verification methods, and learning modalities are also necessary to ensure that learning-enabled autonomous systems are trustworthy and capable of operating in uncertain or evolving operations [170].

Significant developments support RAS's adaptability in **spatial tracking of multiple moving objects in real-time**. This, however, presents challenges around estimates of trajectories of numerous entities based on stable identification and localisation of targets [42, 170]. Nonetheless, other promising **biomimetic (or biomimicry)** approaches modelled on animal and insect neurons (e.g. as bee neurophysiology [202, 203, 204]) are being explored. **Biomimetic autonomous navigation** is one approach to learning-enabled autonomy that promises to develop low-power adaptable and agile control systems, seeking improvements to size, weight, power and cost (SWaP-C) and adaptability. Thus widely affecting military operations enabling real-time data processing and understanding while supporting the miniaturisation trends and enabling **advanced teaming behaviours**. However, new systems engineering, formal verification methods, and learning modalities are also necessary to ensure that learning-enabled autonomous systems are trustworthy and capable of operating in uncertain or evolving operations [42, 170].

Advanced RAS collaborative systems build upon (a federation of) individual agents (whether human, kinetic or non-kinetic) collective capability of adaptable RAS defining, distributing, and executing the tasks and sub-tasks necessary to achieve a common mission within a dynamic and uncertain environment. Furthermore, as collaboration is observed and modelled after nature, swarming in nature becomes an invaluable source of knowledge. For instance, social insects, wolves pack, flies' opportunistic mobbing behaviour, and micro-bacteria and viruses diffusion. Advanced RAS collaboration and swarming behaviour modelling breakthroughs promise autonomous agents and platforms with embedded operational and strategic deployable capabilities relying on basic instructions, decentralised control, and high connectivity requirements.

Advanced Swarming behaviour represents the ability to develop advanced swarm-enabled system architectures for low-cost and rapidly deployable RAS. Particularly, the research in this area focuses on large operationalising multi-domain, non-homogeneous collaborative autonomous teams and human interfaces for control and interaction [42, 153]. For instance, **air-ground vehicle teaming** systems support increased collaboration between land and air units, enabling forward reconnaissance and persistent surveillance. This will be facilitated through adaptable RAS, longer operational ranges, complex 4-D navigation, new launch and recovery methods, and multi-domain operations [42, 153]. On the other hand, **airborne launched systems** as multi-modal propulsion for air-launched UAVs is capable of multi-target tracking and engagement [42, 153]. With larger UAVs, collaborative AI could enable *"loyal wingman"* operational concepts, significantly increasing the effectiveness of individual aircraft and lethality [205]. Additionally, this would allow new distributed warfare concepts for mini and micro-commodity level UAVs, including employing "volley quantities" for large-scale collaborative missions.

RAS Applications

The use of RAS across the battlespace, operational domains, enterprise and industry (especially in manufacturing and logistics) is increasing as costs, adaptability, and miniaturisation improve [206, 207, 208, 209]. There are three trends to note within this space: the increased use and development of collaborative systems, biomimetic micro- and mini-systems, and increased usage across the operational spectrum. Collaborative systems research of interest explores advanced mix-domain autonomous teams, and improved human interfaces for control and collaboration [42, 170, 210]. Other research explores the application of heterogeneous RAS teaming and air-launched systems for independent or cooperative operations [42, 170, 210]. Finally, exciting developments are arising in using RAS systems for specialised environments, such as urban ISR, long-duration underwater vehicles, crewless naval vessels, assisted communication, and supporting operations in subterranean environments [42, 170, 193].

Current policies separate offensive autonomous weapon systems (AWS) (e.g. **LAWS**) from defensive AWS [174]. The international community does not have a consensus on the development of LAWS, mainly due to the ethical considerations around such weapon systems. Despite the lack of international agreement, results in the required technology are continuing. Many technologies for LAWS derive from technologies in nonlethal autonomous systems, which are not subject to the same ethical criticism. Future development of AWS will be based on evolutionary improvements of the current technologies. Investment in technology development includes research in semi-autonomous and autonomous vehicles and weapons systems, though human judgement for targeting and firing capabilities is still the main operating concept.

Among AWS defensive application **crewless naval vessels** have spread in operations in the form of unmanned naval vessels capable of **anti-submarine warfare (ASW)**, operating under sparse supervisory control at global ranges [42, 170, 193]. Potentially augmented with **long duration underwater vehicles**, unmanned underwater vessels can operate in extreme GNSS-denied environments, with little human control, [42, 193]. Similarly, mapping, navigating and operating UxVs in complex subterranean and dynamic terrains (tunnel systems, urban underground, and cave networks) is a challenging and mostly human-based task. Therefore, challenges of managing UxVs in such environments are being explored, focusing on operations in degraded communication environments, autonomous behaviour, and collaborative behaviours.

Hectic S&T breakthroughs in digital and wireless communications will sustain RAS systems deployment and cooperation across mission operation environments - see Appendix D. Instances of **assisted communications** or **mobile aerial radio transceivers** (drone base stations) are already under development [119]. These drones will help existing wireless communications or provide on-demand cellular networks to areas with no communication coverage or have lost such coverage due to conflict, or catastrophe [119, 121, 130]. Furthermore, deploying small UxVs will enable ISR activities on land, littoral, and air in urban areas for defence, security and crisis management.

Micro and mini air vehicles (MAVs) are an emerging aerial platform solution for a broad range of modern military missions, including urban and unconventional warfare, battle damage assessment, tactical intelligence, surveillance and reconnaissance (ISR) [206, 207, 208, 209]. Technology challenges encompass low Reynolds number aerodynamics, the accuracy of analytical and computational models, physical characteristics (e.g. lightweight, speed etc.), adaptive and biologically-inspired multi-functional materials and structures, micro-propulsion and power sources, microsensors and data fusion, robust flight navigation and control systems, miniaturised navigation and control electronics, and system engineering tools.

Micro-robotics is intrinsically tied to micro-autonomous vehicles (MAVs) but is yet experiencing a strong developmental push for the development of micro-RAS, mobile robots with characteristic lengths in the order of 1 mm. These systems are often bio-inspired, exploiting research into muscle-like actuation mechanisms, power-efficient voltage conversion circuits, and origami-inspired design. Use cases include specialised surgical techniques [42, 206, 207].

Likewise, one of the most thought-provoking trends in weapons development is the R&D on **kinetic hybrid weapons**, with the DARPA programs LONGSHOT and GUNSLINGER being two examples [42, 211]. The LONGSHOT program aims to develop a missile-firing missile [211], or more accurately, an air-launched missile-armed UAV, similar to what the European Defence Agency (EDA) proposes as high-performance gun launch and missile propulsion systems. A system with an extended engagement range increased mission effectiveness and reduced risk compared to crewed aircraft [211]. Similarly, the GUNSLINGER program aims to produce a gun-armed cruise missile. Such a hybrid weapon would allow a missile's range, speed, and manoeuvrability with the flexibility and precision of a gun system. Applications are considered close-air support, air-to-air, and counterinsurgency [211, 212, 213]. Both projects rely heavily on Autonomy and AI/ML advances for independent action, target recognition, and engagement.

Human-Machine Teaming

H-M Teaming represents a clear challenge for the Alliance regarding how to spur wet-ware's trust and systems' trustworthiness and establish meaningful human control over autonomous systems while enhancing operations through H-M symbiosis integration.

Research is rapidly expanding the effectiveness of H-M symbiosis, allowing humans and machines to work as colleagues, partners, and teammates. However, this research recognises that humans cannot fully assimilate, understand, and act on the volume of information presented nor control the autonomous collection of that data. Therefore, more effective and natural interactions of AI and RAS systems with humans will significantly enhance operations [42]. Interesting aspects of this work consider determining and signalling the need for human control and how the embedded AI can assess whether the human operator's input can be trusted [214]. Although autonomous systems are integrated and deployed in operations, the question of how and when to initiate human control [214] sits at the edge of human factors, AI, and automation research. In particular, "urgency" assessment by the on-board AI continues to be a weakness of current autonomous systems, especially those used in automotive systems [119, 121, 130, 188, 215, 216]. Moreover, the reverse problem of when or if AI should take over from human control is also of interest in this context and highly related to issues of H-M trust.

Counter-RAS and Resilience

With the increasingly widespread use of UxVs and swarms, research is ongoing to understand how to anticipate and defeat these threats through kinetic and non-kinetic means. While new areas of study, such as swarm-on-swarm engagement, are opening-up in synergy with AI (see Appendix A), E&EM (see Appendix E) and other EDTs.

Given UxVs and swarms, large diffusion, detection and countering unmanned systems and vehicle capabilities shall be highly important. Considering the high pace of development overall and decreasing costs, it is no surprise that RED forces and non-state actors have access to these technologies [107, 217]. Small, incredibly cheap, widely available commercial UAS present challenging targets and a security threat in urban areas. Rapid detection, classification and tracking require improved signal processing software, object-detection sensors and supporting networks to enable cost-effective UAS-on-UAS engagements [42, 119]. Thus, the risk of near, if not equal, use of UxVs capabilities adds urgency to anticipating, mitigating and defeating threats. Considering that **robotic (autonomous) combat vehicle** engagements may be too fast for human control, swarm-on-swarm engagement will be AI-enabled across the kill chain, interfacing with future and legacy defensive systems (kinetic and non-kinetic) to rapidly assess, optimally exploit, and efficiently defeat autonomous enemy systems and swarms [42, 170, 210, 218]. An area for research and study is using **radio frequency redirected energy weapons to counter UxVs**. Likewise, radar sensing and small platform signature modelling contribute to future detection capabilities.

Military Implications

BLUE

UAVs of different sizes and degrees of Autonomy are already used for ISR and strike missions, taking advantage of long loitered times and flexible positioning near potential targets. The long-endurance type of UAVs is particularly important for surveillance when operations are conducted over days. However, the increased use of small swarms of UxVs offers considerable advantages for ISR and offensive and defensive operations. Autonomous systems are expected to lead changes in:

Enable

- **Logistics**: UxVs will transport passengers and cargo onto the battlefield, especially in the relatively small quantities that apply to tactical situations. Current levels of technology may be sufficient to create remotely piloted or autonomous UxVs capable of delivering supplies and ammunition to troops in the field under well-defined circumstances. Wider application within the logistics and transport system will reduce waste, increase operational availability and support warehousing operations.

- **Force Structure**: UxVs and autonomous software agents will replace humans in operational/tactical jobs environments deemed dull, dirty, dangerous or dear (e.g. CBRN, EOD, reconnaissance, etc.). Increased use of autonomous systems will challenge developing appropriate military skills, organisational/force structures and training.

- **Effectiveness**: Employing a *warfighter as a system* concept will see next-generation networks and advanced AI seamlessly integrating disparate techno-human systems into unified and focused capability (e.g. [219]), allowing every *soldier to act as a squad, every ship as a task group, and* *every aircraft as a squadron*. Agile manufacturing (e.g. 3D/4D mix-materials printing) will provide task-tailored systems in theatre on demand.

Prepare

- **Autonomous systems** at large (e.g. innovative robotic and autonomous platforms and systems, including those that are 3D printed, used in novel ways or employing novel designs/propulsion) will increasingly participate in military operations. However, as underlying technologies evolve and spread, continuous investments are needed to establish, prepare and sustain a sufficient and effective presence at the right time. Besides, the ability to build up forces, through appropriate and graduated readiness, to meet any requirements, keeping sufficient flexibility to adapt to possible changes in the strategic environment. These also include the capabilities to contribute to Deterrence and Defence, Resilience and Projecting Stability.

Project

- **Lethality**: Large numbers of low-cost systems and improved human-machine teaming will greatly improve force projection. This will enable the capability to gather constant and reliable information over vast geographical areas in much greater detail than ever. An armed UAV would provide air combat capability without exposing a pilot to risk. The UAV could carry ordnance, or the UAV itself could be integrated into the aircraft like an air-launched cruise missile. UAVs can attack high-value, sea or ground targets in military operations. Through a *loyal wingman* concept, current air, land (e.g. [219]) or naval assets could act as a *shepherd* for several assigned UxVs, especially in an area denial or Anti-Access/Area Denial (A2AD) role.

Engage

- **Cyber**: Autonomous software agents will increasingly undertake cyber (offensive and defensive) operations.

- **Swarming**: UxV swarms will enable new sensing and attack paradigms for friendly forces (e.g. [220]). One approach is to use a swarm as an expendable asset, for example, to penetrate defended areas through the saturation of defences or to protect BLUE critical assets through large numbers of sacrificial sentinels. Ultimately, it will cost more time, energy and money for RED to defend against a swarm than to overcome it.

Protect

- **Counter-measures**: The wider use of UxVs and swarming on the battlefield will require additional force protection assets with explicit counter-UxV capabilities. These will span the spectrum of hard and soft kill options, such as electronic counter-measures, cyber, kinetic kills, directed energy weapons, interceptor swarms, and deception. It will be necessary to defend critical assets from swarms, where each node in the swarm is highly manoeuvrable, adaptable and hard to detect. Counter-swarm techniques must engage each node quickly and cost-effectively to defeat the swarm.

- **Autonomous decoys**: The use of autonomous systems as decoys, protection behaviours for systems and humans, and human-machine teaming for protection must be more fully explored. Furthermore, counter AI-Autonomy-enabled adversaries' capabilities are becoming increasingly important.

Sustain

- **Sustainability**: A combination of agile manufacturing and autonomous systems may enable automated logistics support in dangerous or isolated operational environments. Reduced manning may also substantially diminish costs, with commensurate changes required in training and military occupations.

- **Survivability**: Reduction in combat casualties (due to smaller forces), more immediate medical care, and greater operational effectiveness. It is conceivable that UAVs will conduct future combat search and rescue missions, further increasing survivability.

Inform

- **Urban Operations**: Micro-UAVs will increase situational awareness in complex urban areas. These vehicles can also perform regular or special operations in unconventional or asymmetric threat environments, providing ISR and target acquisition capabilities in complicated operations. Such vehicles could provide real-time data, directly support command decision-making processes and would reduce the risk for the warfighter.

- **Situational awareness**: Improved ISR through widely dispersed, persistent, low-observable vehicles/sentinels employing a broad range of low-power sensors (EO/IR, radar, magnetics, etc.). Increased use is expected in evolving operational areas such as space, cyber and urban domains. For example, hand-carried micro-UAVs deployable by soldiers in urban domains will be available and widely used. UAVs of different sizes and degrees of Autonomy are already used for ISR, taking advantage of the fact that UAVs can have long loiter times and be positioned flexibly near potential targets. Long-endurance UxVs are particularly important for surveillance when operations are conducted over days to years. Cyber agents will also increasingly be used to maintain situational awareness within virtual spaces (social or otherwise) and to identify threats or vulnerabilities.

C3

- **Manoeuvrability**: Increased tactical and operational agility through increased presence, numbers (swarms) and reduced logistics needs. Automated systems will be able to exploit tactical opportunities consistent with operational direction rapidly.

RED

Peer or near competitors will leverage the same advantages, potentially cancelling the organisational and operational value of Alliance autonomous forces. Their use in covert hybrid war operations could provide plausible deniability while achieving tactical, operational or strategic objectives. As costs to produce autonomous systems decrease, their use and employment by non-state actors will increase in number and effectiveness. Current counter-measures need to scale or adapt better to the broad operational use of large numbers (swarms), small or cheap, widely dispersed autonomous systems. Various approaches exist for countering Alliance autonomous systems, such as cyber-attacks (platforms or C2); electronic warfare; counter-swarms; or directed energy weapons. RED may also employ small UAVs in targeted attacks against individuals [221] or increase the effective disbursement of CBRNE materials [220].

Technologies supporting (limited) swarming are becoming widely available. They are no longer beyond the technical capabilities of non-state actors (e.g. the Yemen-based Houthi movement's 2019 attack on Saudi oil facilities [222, 223]).

Figure B.1: *Interoperability Challenges.*

Interoperability

Since the previous iteration of the present report [2], the Alliance and Partner Nations integration of autonomous systems continued steadily, robustly moving from laboratories to field testing toward a wide portfolio of application areas. As a result, such systems are expected to be omnipresent in Alliance operations.

Among the main enzymes in the integration and operability of unmanned systems, interoperability outlines the synergies and convergence among heterogeneous technological systems to use solid interoperable platforms for future warfighting capabilities [224].

Tough, interconnected and integrated multi-domain systems represent a must in tomorrow's operational environment. Command, control and communication (C3) of and among autonomous systems across domain issues through unified, agile and common architecture are still under resolution. Meanwhile, autonomous solutions are increasingly diffusing among non-state actors and red forces, raising concerns about the democratic, ethical, moral and legal use of RAS. Moreover, robust synergy in C3 operating protocols and common platform architecture are cornerstones for establishing resilient data links, integration and symbiotic systems as well as H-M interactions (e.g. collaborations, take-over and parent/hierarchical relationships, data shareability, and fusion). Evolutions in TEVV and VVA shall enhance trust in the system, thus strengthening symbiosis, platforms cooperation, systems modularity, and interchangeability.

S&T Development

State of Development

Advances in Autonomy and RAS will drastically shift warfighting concepts as a compelling force multiplier. Autonomy will greatly increase the efficiency and effectiveness of both manned and unmanned systems, providing a strategic advantage for the Alliance. RAS will significantly and increasingly enhance, threaten, and enable NATO's current and future operational capabilities over the next 20 years. More generally, Autonomy research areas are highly interdisciplinary and dependent on synergies with other EDTs, spanning systems designs, sensing, interfaces, counter-measures, human control and application.

Data

BDAA and Sensors data naturally fuel RAS's ability for decision-making and operations management and execution. The importance of Situational awareness, (blue) forces tracking and (red) monitoring, as well as real-time coordination of swarms, heavily relies on harvesting insights from sensor data, drone data, and other grid data sources. Thus supporting and augmenting ISR capabilities.

AI

See Appendix A.

Space

RAS are already deployed in the space domain of operation, as in any other, as a mega-satellite constellation. However, weak signals of UxVs are sprouting in advanced task support applications. For instance, the US Space Force deployed dog-like RAS quadruped unmanned ground vehicles (Q-UGVs) to support damage assessment and patrolling tasks [225]. Furthermore, as the research and science advance, RAS will further enable Space capabilities (e.g. in-orbit servicing (IOS) - see Appendix J) while more generally, Autonomy will enable advanced RAS-Space assets decision-making.

Quantum

See Appendix I.

BHET

Synergies among biotechnologies in the applied medical science and micro-RAS systems within the miniaturisation trend are reaching unexpected payoffs such as half-millimetre size robots with the promise to perform a task in confined environments (e.g. the human body) [208]. On the other hand, instances of robots (semi- or fully-)autonomously performing surgery are auspiciously becoming a reality [226].

Materials

See Appendix H.

Energy

Smart grid generally enables and benefits from other EDTs [227], as already discussed in Appendix F. Besides, commercial layered smart grid applications, in combination with RAS and AI, are currently unlocking completely autonomous power plants, though a military-applicable concept is yet to be seen.

E&EM

E&EM and RAS counter-measures will intrinsically develop in parallel, enabling capabilities and counter-measures to RAS-enabled adversaries' capabilities. For instance, kinetic and directed energy weapons (DEW), electromagnetic UAVs, and swarm counter-measures.

STO Activities

Several STO Scientific and Technical Committees have produced significant research on RAS (or *Autonomy*) and autonomous technologies. Many panels have ongoing activities on several topics aligned with these technologies. The following is a sample of ongoing activities:

- AVT-341: Mobility Assessment Methods and Tools for Autonomous Military Ground Systems
- AVT-ST-009: Technical Support to NATO Next Generation Rotorcraft Capability (NGRC)
- HFM-311: Cognitive Neuroenhancement: Techniques and Technology
- HFM-330: Human Systems Integration for Meaningful Human Control over AI-based systems
- HFM-332: Development and Implementation of Autonomous Transport and Medical Systems for Casualty Evacuation
- HFM-365: Human Capability & Survivability Enhancement: Augmenting people to deliver an enhanced and more resilient capability for defence
- HFM-AVT-340: Neuroscience-based Technologies for Combat-oriented Crew Cockpit Design and Operations
- IST-169 (AI2S): Robustness and Accountability in Machine Learning Systems
- IST-179 (AI2S): Interoperability for Semi-Autonomous Unmanned Ground Vehicles
- SAS-140: Directed Energy Weapons Concepts and Employment
- SAS-143: Agile, Multi-Domain C2 of Socio-Technical Organizations in Complex Endeavors
- SAS-157: Automation in the Intelligence Cycle
- SAS-159: How could Technology Development Transform the Future Operational Environment
- SAS-160: Ethical, legal and moral (ELM) impacts of novel technologies on NATO's operational advantage – the "ELM Tree"
- SAS-175: Integration of Unmanned Systems (UxS) into operational units
- SCI-307: FAMOS Framework for Avionics Mission Systems
- SCI-310: Expanded Counter-measure Methods against IR Anti-Ship Threats in Varied Parameter and Scenario Engagements Using all-digital Tools Sets
- SCI-312: EO-IR Countermeasures
- SCI-321: UAV Applications for Military Search
- SCI-326: Electronic Support (ES) Techniques Enabling Cognitive Electronic Warfare (EW)
- SCI-327: Counter-measure Concepts against Anti-Aircraft Dual band EO/IR Imaging Seekers
- SCI-332: Radio Frequency-based Electronic Attack to Modern Radar
- SCI-342: Explosive Ordnance Disposal (EOD) Tele-manipulation Robot Technology Roadmap Development
- SCI-343: Enabling Federated, Collaborative Autonomy
- SCI-354: Air Platform Generic Self-Defence
- SCI-SET-353: C-UAS Mission-Level Modelling & Simulation
- SET-272: Automated Scene Understanding for Battlefield Awareness
- SET-307: Advanced radar techniques for robust situation awareness and threat assessment considering Class I UAS in complex environments
- SET-311: 10th Military Sensing Symposium (MSS)
- SET-315: Detection, Tracking, ID and Defeat of Small UAVs in Complex Environments
- SET-307: Advanced radar techniques for robust situation awareness and threat assessment considering Class I UAS in complex environments
- SET-310: Assessment of EO/IR Compressive Sensing and Computational Imaging Systems
- SET-311: 10th Military Sensing Symposium (MSS)
- SET-313: Advanced Methods for Hyperspectral Data Exploitation
- SET-315: Detection, Tracking, ID and Defeat of Small UAVs in Complex Environments
- SET-317: Multi-dimensional/Multi-platform Radar Imaging
- SET-318: AI/ML and Cognitive Radar
- SET-HFM-314: Multi-Omic Data Sciences Research Workshop

Scientometric Analysis

The keywords associated with this Autonomy and RAS as derived from STEAM analysis are shown in Figure B.2.

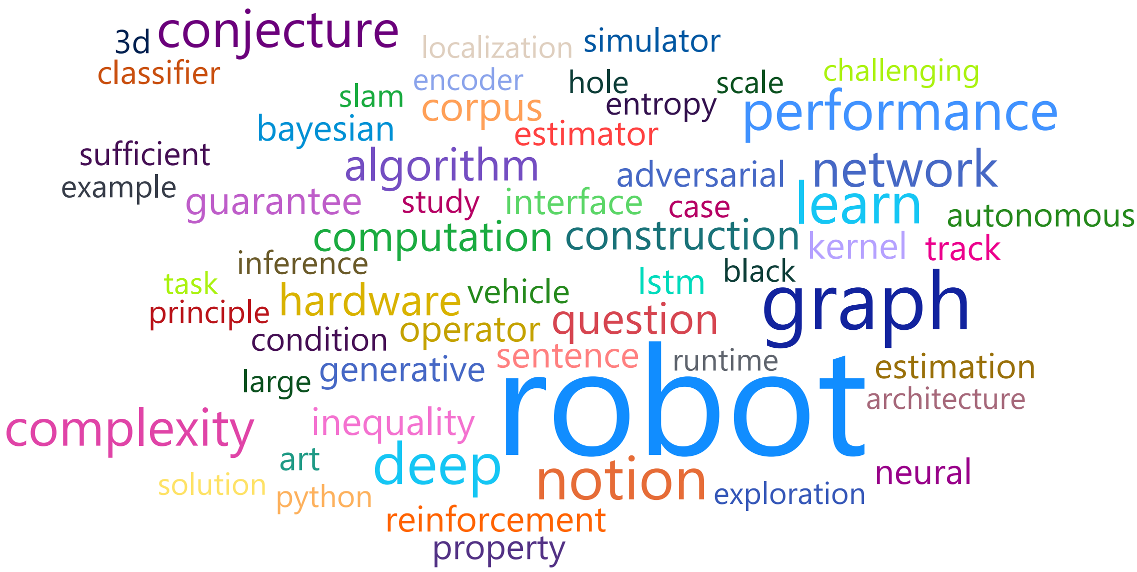


Figure B.2: *STEAM - Robotics and Autonomous Systems - Keywords*

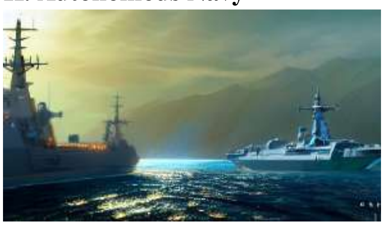
Survey Results

The following table presents the assessed potential impact, state and rate of development and identifies areas for focused research.

Table B.3: *Robotics and Autonomous Systems (RAS) 2023 - 2043.*

EDT	Technology Focus Areas	Impact	TRL	Horizon
RAS	Counter RAS	High	3-4	2030-2035
	Enhanced RAS	High	5-6	2025-2030
	Human-Machine Teaming	High	3-4	2030-2035

Conjecture Card: Robotics and Autonomous Systems

A. Access Inaccessible Areas  Access contaminated, high-threat or inaccessible environments to identify risks and MEDEVAC casualties without, necessarily, requiring human supervision.	**B. Use Commercial Systems**  Take control of or piggyback off commercial unmanned systems for own purposes.	**.C. Replace the Soldiers**  Complement human forces with human-like robots that have beyond human strength and information processing ability.
D. Cyber Immune System  Employ cyber agents capable of the immune system like independent identification, monitoring and response to cyber-physical network attacks.	**E. Sustainment**  Summon unmanned refuelling or strategic logistics on demand, deployable in air, maritime or land environments.	**F. Autonomous Lethal Weapons**  Automatically attack specific individuals, vehicles, objects or facilities with wasp-sized or smaller systems.
G. Deploy a Swarm  Infiltrate or disrupt adversary actions or conduct surveillance using massive swarms (e.g. millions of nano-UAVs) at sea, on land or in the air.	**H. Active Defence System**  Automatically defend unarmoured or lightly armoured vehicles or individuals from various incoming threats via automatic countermeasures systems.	**I. Driverless Transportation**  Travel anywhere, including urban areas (sea, air, littoral, near-space and ground) in unmanned vehicles ranging in size from personal transporters to strategic lift.
J. Intelligent Smallsats  Embedded satellite AI allows a flexible response to threats, manoeuver, collection and power optimisation.	**K. Autonomous Navy**  Naval task forces are increasingly uncrewed, multi-domain and autonomous, with limited numbers of manned platforms.	**L. Loyal Wingman**  Human wing-men for aircraft are replaced entirely with autonomous systems.

C. Biotechnology & Human Enhancement

> **Biotechnology and Human Enhancement**
> "I think the biggest innovations of the 21st Century will be at the intersection of biology and technology. A new era is beginning." - *Steve Jobs* .

Definition

> **Biotechnology & Human Enhancement Technologies (BHET)**
> *Biotechnologies* use organisms, tissues, cells or molecular components derived from living things to act on living things themselves or by intervening in the workings of cells or the molecular components of cells, including their genetic material [228]. Biotechnologies can also act on inorganic materials; *Human Enhancement Technologies* (**HET**) are biomedical interventions that are used to improve the human form or to function beyond what is necessary to restore or sustain health. HET may enhance physiological, cognitive or social functions.

Keywords

Medicine · Supplements · Mixed Reality · Prophylaxis · CRISPR · Synthetic Biology · Human Enhancement Technologies (HET) · Bio-Engineering · Genetics · Medical Countermeasures · Genetic Engineering · Micro-Fluidics · Neural Interface · Prosthetics · Exoskeleton · Molecular Engineering · Brain-Machine Interface · Neural Prostheses · Neural Interface · Biosensors · Bioinformatics · Micro-Arrays · Bioelectronics

Overview

Biotechnology is *"a broad discipline in which biological processes, cells, or cellular components are exploited to develop products and new technologies for specific purposes"*. A related research area is that of Human Enhancement technologies, *the process to augment physical form or cognitive, physiological, sensory, or social functions beyond baseline performance.* Both are essential elements of human health science, itself defined as the *application of science to human health issues, encompassing many such sub-disciplines such as nutrition, medicine, physiology, psychiatry, etc.*

In defence circles, biotechnology is frequently associated with pathogens, weapons of mass destruction and health and medicine, but biotechnology influences much more. Biotechnologies are multidisciplinary and cross every military domain. They fuse technological and engineering advances with the natural world to provide novel solutions to complex problems. While biotechnologies are and will be developed largely to benefit humankind and the planet, many technologies are unfortunately dual-use in nature and may be considered controversial or counter to the ethical, legal, social, and moral code of certain nations or groups. Hence acceptance and adoption of these technologies will vary according to societal ethics and norms.

Biotechnologies have historically been and are expected to be increasingly disruptive over the next 20 years. As noted in [229] *"Today's tech wave, driven by digital technologies, is now cresting. The next tech wave, building on digital breakthroughs, is in the physical and biotechnical domains. The states and companies that harness this wave of "ABC" foundational technologies atoms, bits, and cells – will win the future."* . Innovation in biotechnologies is seen to be in [230]:

- Biomolecules: Engineering intracellular molecules;
- Biosystems: Engineering cells, tissues, and organs;
- Biomachine Interfaces: Connecting neural systems to machines; and
- Biocomputing: Using cells and cellular components for computation (or storage).

The range of biotechnologies and fields of application is extensive and will provide powerful defence and security capabilities over the next two decades. While they will reduce costs and increase flexibility, at the same time, biotechnologies also hold the potential to increase the threats faced by Allied forces. Biotechnology and genomics are advancing rapidly in the short midterm. Presently, the primary drivers of innovations in biotechnology arise from the civil sector but can easily be transferred to the military sector where appropriate. Thus, it will be critical for NATO and governments, in general, to coordinate and collaborate with their civilian counterparts closely.

Figure C.1: *Modern Vitruvian Man.*

Biotechnologies have historically been and will continue to be genuinely disruptive, mainly in the near-term, as they apply to human health issues. Nevertheless, this promise is often oversold [230] as human and biological research is necessarily constrained by physical, natural, ethical, legal, and moral constraints [231, 232, 233]. Highlighting once again Amara's law, there is a tendency to overstate the maturity of biotechnology. Its general availability is often overestimated when conceptualising novel innovations such as personalised medicine, Human-Machine Integration (HMI), and direct neuro-interfaces between *"wetware"* and *"hardware"* (e.g. biological and physical). Conversely, biotechnology's potential long-term risks and significant benefits are often misunderstood (e.g. COVID-19 vaccine developments).

Advances in materials, information systems and the human sciences set the stage to significantly enhance human capabilities, pushing the physiological, cognitive and social human performance frontiers. Rapid parallel developments in RAS, AI, BDAA, miniaturisation and innovative materials/manufacturing enable R&D in these areas. As a result, BHET developments are moving at a breathtaking rate, driven by research breakthroughs (e.g. the discovery of CRISPR/Cas9 for gene editing [234]), substantial national investments and increasing commercial interest. However, the limits on development are around the need for baseline research and ethical, legal and policy concerns. In particular, there are serious issues around genetic engineering; environmental impact; the release of personal bio-data; pharmacological enhancements; and ethical testing of new therapeutics and countermeasures.

Manipulation of our biological environment and human enhancement goes back to the earliest days of humankind when our ancestors employed skins, stones and agriculture to create an evolutionary advantage. However, biotechnology and human-enhancement technologies (BHET) are expected to be available over the next 20 years, changing our very definition of being a soldier, sailor or aviator. These technologies span the spectrum of biological sciences: Genetic manipulation (e.g. CRISPR) to develop novel pathogens or medical countermeasures; Manufacturing methods exploiting biological processes; Human enhancement via integrated robotics (e.g. exoskeletons or replacement parts); Neural interfaces; Enhanced vision; Socio-technical symbiosis with AI and autonomous systems; Pharmacological approaches to cognitive and physical enhancement; Increased virtualisation of the socio-cognitive environment supporting the development of new social, information and organisational structures; and, New bio-sensors and bio-informatics will increase our understanding of socio-cognitive, physiological, economic and neurological behaviours to improve operational performance and resilience and increase the effectiveness of non-kinetic targeting.

Biotechnology and next-generation human enhancement technologies are in their infancy. However, some commentators have stated that building on the information and (artificial) intelligence revolutions we have already experienced, the next revolutionary technology cycle will be (synthetic) biology-based. The need for NATO to adjust to this new environment (however it may develop) and the capabilities and threats it will engender are not trivial. Of all the strategies and implementation plans NATO expects to deliver over the next few years, biotechnology and human enhancement technologies will be the most challenging.

Disruptive BHET research areas of potential interest to NATO are presented in the following subsections.

Biowarfare and Heath

Specific areas of interest are:

- New technologies and science for pathogen detection/identification.
- Stopping pathophysiologic processes of bioagents.
- New drug classes (e.g. performance and antibiotics).
- Outpacing and preventing disease.
- Biometrics.
- Wound care and regeneration.

The development of new *Medical countermeasures* and more generally *Biomedical Technologies* pulls together and applies parallel developments in bioinformatics, biosensors, human augmentation and synthetic biology. For example, applied research in casualty care and neural interfaces will help to support evidence-based medicine, operational readiness, increased immunocompetence, disease/biothreat forecasting & detection, patient-centric medicine, the rapid development of CBRN countermeasures, improve rehabilitation through new neural interfaces & AI-enabled robotic prosthetic limb technology, and provide new diagnostic and treatment options for mTBI (mild traumatic brain injury) and PSTD (post-traumatic stress disorder) [170].

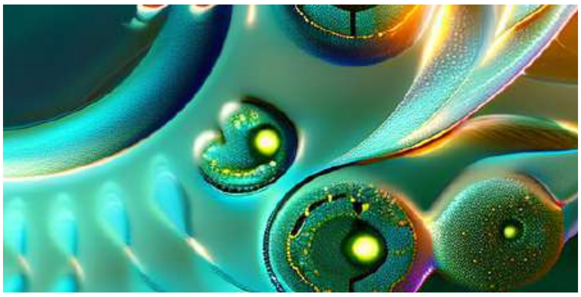
Novel biological and chemical agents pose a new threat to the Alliance and will require constant efforts to ensure adequate defence. Hostile actors can create new biological and chemical weapons, or modified organisms may accidentally escape a research facility. Pre-existing detection methods and medical countermeasures will likely be inadequate for agents never seen and encountered before nor to defend against these novel threats. Biotechnologies will allow new detection/identification technologies for a variety of CBRN threats. Given these threats, the chemical and biological defence components of NATO Nations have been early adopters of synthetic biology. Examples include vaccines and therapeutics, next-generation textiles, and novel pathogen agnostic detection/identification methods.

- The regular introduction of new pathogens would put an unprecedented strain on global vaccination resources.
- The personalisation of biological weapons allows the targeting a specific individual's DNA.
- Food and water safety testing methods are often agent-specific and, therefore, not suited for detecting novel agents in the food chain, as could occur in a deliberate contamination incident.

Combat casualty care may also be significantly enhanced through improved bioinformatics and biosensors, remote monitoring, molecular & cellular biology, AI for rapid diagnostics, bioinformatics, surgical techniques & tools, and novel materials to improve quick identification and treatment of tissue damage and infection. These technologies have the potential to significantly reduce mortality and morbidity resulting from injuries on the battlefield, improve the efficacy of follow-on care and enhance rehabilitation efforts.

Fundamental research is also ongoing in understanding the dynamics of complex biological systems, such as the human biome. Research focuses on understanding complex dynamic biological systems-of-systems and developing mechanisms for assessment and optimal control [170].

Genetics and Microbiology



Advanced biotechnology tools, such as genetic engineering and synthetic biology, provide new capabilities and will increasingly influence and impact warfighters and societies in various ways, some of which are unconventional. Recent genetics research has focused on developing personalised medicines and curative/preventive treatments for diseases, to include genetically modifying disease organisms themselves eliminating their ability to sicken humans and other organisms. Weak signals in this area suggest an increasing role for genomic information in the health care of military service members and its integration into the continuum of military medicine. The use of gene-editing technologies such as CRISPR-Cas9 – an enzyme capable of cutting DNA strands- has focused S&T investigation on other or similar gene-editing tools and means of mitigating accidental or deliberate misuse of gene editing.

Significant advances are emerging and expected to mature over the next 20 years in the available technologies to obtain genomic knowledge that will help accelerate genome-based discovery for medical and biotechnological applications. These represent advances in the broader field of bioinformatics which is discussed as a separate area in more detail below. However, the trends described here are those that apply mainly to the areas of genetics and microbiology: Interesting research is ongoing in protection against gene editing, alternative gene editing technologies, next-generation genomic sequencing, metagenomics, and de novo gene sequencing.

Bioengineering and Biomanufacturing

Bioengineering describes applying engineering principles of design and analysis to biological systems and biomedical technologies. Emerging research is pursuing new approaches (often AI/ML-enabled) to engineer complex, multicellular methods (e.g. reproducing xenobots) for enhanced capabilities and functional materials. Technical progress is also being made in the tools and techniques available for engineering biology. Bioengineering developments will deliver unique and creative applications of engineering principles to analyse biological systems, exploit them (e.g. biomanufacturing) and solve problems in the interaction of such systems.

Bioengineering is expected to become significantly easier and cheaper over the next twenty years, with new developments reducing the biotechnology transaction costs in gene reading, writing, and editing. In addition, emerging research efforts are refining and extending the ability to engineer complex, multicellular systems for enhanced capabilities and functional materials with integrated biological functions. This includes 3D bioprinting, AI/ML-enabled bioengineering, hybrid materials, synthetic bio-mimetic materials, smart materials, and organoids.

One aspect of bioengineering is biomanufacturing. Biomanufacturing utilises organisms, components thereof, or biological processes to produce commercially important molecules and products in the agricultural, food, energy, material, and pharmaceutical industries. Biotechnology provides next-generation materials previously unattainable through traditional industrial chemistries, and biological manufacturing often produces fewer toxic by-products than traditional chemistries, providing cleaner chemical sourcing. While biomanufacturing is advancing rapidly, the science continues to outstrip regulatory frameworks. This is a challenge for the setting of norms and standards.

For example, biotechnology is increasingly replacing oil refining to make commodity chemicals, including energetics and propellants. It has been reported that two-thirds of the world's most used chemicals could be synthesised from renewable raw materials, reducing reliance on fossil fuels. Microbes grown in fermentation vats are already being trained to produce these chemicals, and synthetic biology allows for making previously unattainable chemicals. Biomanufacturing is attractive to industry because of the low capital expenditure to build a facility, and bio-foundries can fairly easily switch from one product to another with little investment aside from seed stock since the same equipment can be used to produce a variety of chemicals even though they are sourced from different organisms.

Another area that is increasingly influenced by biologics is adhesives production. Organisms have perfected the ability to adhere to various surfaces in various environments. Scientists are taking their cues from these secretions and mimicking the compounds, producing sometimes stronger and less caustic adhesives for multiple purposes.

Biomanufacturing is not only limited to chemicals. One day, biological components may also be utilised for military construction. For example, government and industry teams are already investigating a technique for turning sand and soil with a bacterial additive into durable, hard surfaces, potentially strong enough to serve as transport aircraft runways [235]. This would expand the ability to project power, reduce the heavy machinery required to establish basing in new environments, and alter the future of warfare.

Not only can biological organisms be utilised to generate chemicals and novel materials, but they can also protect against the degradation of structures and equipment. Employment of biotechnologies can extend service life and reduce the resources required to maintain facilities, platforms and equipment. Particularly challenging for maritime operators is combatting biofouling by biofilms [236]. Biofilms are layers of microorganisms that form slimy coatings on wet surfaces, including the hulls of ships. Due to increased drag, they cost the shipping industry and naval fleets billions of pounds each year in cleaning costs and extra fuel [237]. To put this in perspective, the estimated cost of hull fouling for the Arleigh Burke-class destroyers (DDG-51) is 1 Billion USD over 15 years [238]. In the future, microorganisms that naturally deter the aggregation of cells forming biofilms may be embedded in marine coatings, reducing fuel costs and lost sea hours caused by ships needing to be dry-docked for thorough cleaning.

Similarly, microbes can be embedded into coatings or developed as after-market sprays to prevent corrosion. Moreover, concrete buildings, bridges and roads may soon be able to repair themselves after the first signs of degradation. Researchers at Binghamton University have merged biotechnology with structural engineering. They have incorporated dormant fungal spores into a concrete matrix, which revive when exposed to water and oxygen permeating through the cracks [239].

Synthetic biology involves the precise genetic manipulation and engineering of organisms for scientific research and developing unique characteristics and capabilities not seen in nature. Synthetic biology is a multidisciplinary science that allows the design and building of biological components, systems or organisms. Furthermore, synthetic biological processes can yield new organic molecules, novel materials that cannot be manufactured directly or even new bio-manufacturing paradigms. Synthetic biology builds upon a human tradition of genetic manipulation (e.g. crop breeding, domestication, etc.). Still, it has begun to evolve rapidly due to the confluence of molecular biology, systems engineering, information science and other emergent technical fields.

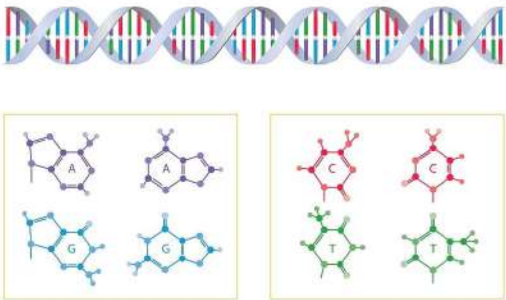


Figure C.2: *DNA.*

The complex convergence of several fundamental technical domains, such as molecular biology, systems engineering, etc., precludes a concise and comprehensive characterisation of all relevant and enabling science and technology in synthetic biology. Synthetic biology is not a single technology but rather an integrated environment of synergistic technologies (e.g. CRISPR/Cas9 [240]) involved in the manipulation of DNA sequences and exploitation of the resulting complex molecules. The latter involves specialised bio and chemical engineering for scaling biological processes to produce meaningful quantities of new organisms and their products. The former includes the involvement of data and information sciences to architect new molecules. The technologies involved in synthetic biology are becoming more advanced and refined globally as public and private sector investments are increasingly applied to this field in pursuit of economic and national security objectives.

Biological engineering is a developing area of research that holds significant promise. Biological engineering aims to design and construct multicellular biological systems or systems-of-systems, including AI and genetic design. The goal is to create biological materials with engineered properties. Developments in this area include AI-optimised xenobots (e.g. specialised bio-robots) for nano-scale manufacturing [241, 242] and living bio-sensors (e.g. persistent living aquatic or terrestrial sensors, or CBRN monitoring) [170].

The scope and magnitude of the future contributions that synthetic biology will make to civil and national security sectors are currently quite speculative; however, there is little doubt that this technology domain will have substantive impacts wherever it is applied or exploited. Examples of practical applications of synthetic biology are the development of new macro-phages [243], plants, and insects [244]; virally constructed batteries [245]; and *xeno-bots* for nano-scale manufacturing [241, 242]. Nevertheless, many technical barriers remain to be overcome to realise their full hypothesised potential, and many ethical and institutional challenges to be mitigated. Moreover, the broad global awareness and proliferation of the underlying enabling technologies for synthetic biology largely preclude its comprehensive control; potential adversaries and economic competitors can be expected to have few if any, barriers to its exploitation for their national or organisational objectives.

Systems Biology and Bioinformatics

Systems biology is an approach to interrogating complex biological systems through large-scale quantitative analysis of the dynamic interactions among several components of a biological system. Areas of particular interest are novel CBRN biological sensors and computational biology. Enabled by advances in *Data*, AI, Autonomy, and potentially Quantum, this systems approach, and the associated bioinformatics advances in this area, will enable other biotechnology and human enhancement technologies (BHET). Understanding the fundamental process of biological networks, leveraging big data analytics and AI, and developing new CBRN sensors are just some areas that are expected to mature over the next 20 years.

Data and AI are key enablers of biotechnologies, especially synthetics biology, bioengineering and biomanufacturing. As noted by the evolutionary biologist Richard Dawkins [246] *"I'm fascinated by the idea that genetics is digital. A gene is a long sequence of coded letters, like computer information. Modern biology is becoming very much a branch of information technology."*

Bioinformatics, and the related field of computational biology, is concerned with the storage, retrieval, organisation and analysis of biological data, particularly associated with humans or human activity. Processing large volumes of data available for exploitation and assessment (often in real-time) has enabled a much greater understanding of biological, biochemical, physiological, cognitive and social behaviours. This has supported new technological developments in medicine, genetics and biology. Especially over the last 15 years, bioinformatics has transformed the biological sciences to the point where:

> *"It might be that a new, "theoretical biology" is emerging, where models and their predictions can now be assessed by experimental biology, in analogy to the interplay between theoretical and experimental physics. This moment might have come faster than expected. The merging of computation into the fabric of biosciences and biomedicine by 2020 ...will possibly necessitate a redefinition of computational biology as a distinct discipline in the not-so-distant future." [247].*

Biosensor developments (especially cheap and widely available ones) have significantly contributed to this data explosion. Biosensors measure biological (immunological, pressure, thermal, etc.) or biochemical processes and convert them into electrical signals. These are widely used today and come in many forms. They may be employed for many purposes, such as nano-sensors embedded in smart clothing for detection of CBRN agents; treatment monitoring (e.g. diabetes); silicon photonic biosensors (e.g. fibre Bragg gratings [248]); rapidly applied *tattoos* to monitor physiological or cognitive stress [249]; and in support of biomedical research [250]. Human physiological monitoring technologies are already commercially available, and more advanced sensor packages will mature in the midterm. In addition, advances and technological convergence in material, information and human sciences are allowing new cheaper, smaller and more robust biosensors to be developed.

S&T development in bioinformatics and biosensors, as they related to NATO capabilities, will be predominately around their novel use, application of new analytical methods (e.g. AI, quantum biology [251], new sensors (in vivo / ex vivo) and the identification of new biomarkers). This continued development will support predictive combat casualty care and diagnostics; operational readiness (e.g. over-training, nutritional deficiencies, immunocompetence, cardiac health and muscular-skeletal injury); and assessment of CBRN exposure.

State-of-the-art sensors are typically designed for optimal detection only. For example, terrorism threats and military conflicts have motivated research into novel sensors for detecting explosives and chemical warfare agents (CWAs). The focus of today's research on (bio)sensors goes far beyond optimising the sensing material; it includes the ability to make decisions and act – *smart sensing*. Research in this area includes the application of [252]: sensor material designs employing carbon nanotubes, polymer nanowires, and porous silicon; machine learning, and DNA-based molecular computing for smart biosensor function; and, bioelectronics and microelectronics, such as nerve cell microelectrode arrays for creating novel transducers and physiological biosensors.

Enhanced bioinformatics and biosensors will improve monitoring and bio-situational awareness through advanced data collection and predictive analytics. Leveraging such techniques will support improved military health, operational readiness and training through predictive and pre-emptive responses to environmental or individual issues [170].

Long before the advent of modern computers, organisms have been storing in their tissues the blueprints to their construction and the instructions for their growth and physiological processes. Under the right conditions, deoxyribose nucleic acid (DNA) can persist for thousands of years and be shared with other organisms. Instead of 0's and 1's, DNA utilises A's, G's, C's & T's, giving rise to single-celled creatures and behemoths of the sea. Not only can DNA store information regarding living organisms, but scientists have also utilised this media to store digital information. Researchers have encoded gift cards into DNA and reconstituted them to buy books, while scientists from Harvard have even stored a short movie clip in living bacterial DNA and were able to recall the information [253].

Humans have long used animals to detect toxic/dangerous substances and locate humans or other organic substances. However, organismally-based sensors have advanced far beyond the traditional "canary in a coal mine" model for detecting carbon monoxide. Biotechnology advances have contributed to the large range of sensors that employ microbes or single animal cells as their enabling components. Similarly, a new class of engineered living sensors (ELS) is being developed from plants to multicellular animals to improve the detection of specific targets and provide better situational awareness in specific environments [153]. Of primary concern is ensuring ELS do not escape from their intended environment or irreversibly perturb the natural environment. Furthermore, organisms have evolved to survive in a variety of environments and subsist on a variety of substrates. The digestive mechanisms of these organisms can be utilized in bioremediation efforts from cleaning up oil spills [254] to degrading plastics [255].

Human Enhancement

Human augmentation, human enhancement, or soldier systems are broadly understood to mean technologies used to improve human form or to function beyond what is necessary to restore or sustain health. Concerning BHET relevant to NATO, we take these to cover the range of human domains - physiological, cognitive & social, and the use of robotic exoskeletons, smart textiles, drugs, and seamless man-machine interfaces.

The development of new human augmentation technologies (physical, pharmacological, neurological, or social) can significantly change the capabilities of the individual soldier, sailor, or aviator significantly [256, 257, 258, 259, 260] and create integrated human-machine symbiotes of unparalleled capabilities. Examples of such augmentation across a variety of sensory modalities are [256]:

- Ocular enhancements to imaging, sight, and situational awareness through implants, glasses or contact lenses. These visual enhancements will support team data sharing; enhanced target identification; man-machine teaming; and expansion of vision beyond the visible spectrum [261]:
- Restoration and programmed muscular control through an optogenetic bodysuit sensor web;
- Auditory enhancement for communication and protection; and
- Direct neural enhancement of the human brain for two-way data transfer.

The first three technologies are expected to be widely available within 20 years. The last, direct neural enhancement, is potentially the most disruptive but is also likely to be widely available in 2050, putting it outside the scope of this study. Nevertheless, developing direct neural-silica connections supporting bi-directional data transfer and mesh networks is a real possibility. Given recent advances in understanding the brain's neurological components and cognitive architecture, neuroelectronic components that can efficiently implement brain-like algorithms and interface directly with biological *wetware* offer possibilities for new technological capabilities that could significantly impact both the civilian and military domains. Very high-speed, very low-power neuromorphic electronic components that feature non-von Neumann architectures and analogue-like processors offer the possibility of autonomous systems and heterogeneous computer architectures that incorporate these devices. Such systems could perform tasks that the brain excels at but currently thwart classical computers, such as extensive heterogeneous data analysis and visual scene processing. Interfacing these devices with biological systems will offer new treatment methods for neurological diseases and improved interface mechanisms between the brain and electronic devices to better control artificial limbs.

Ethical, legal, and policy issues arise around the entire spectrum of human enhancement technologies, but especially with pharmacological enhancements. As noted by [262]:

> *"Militaries have long sought to directly enhance warfighters' physical and cognitive performance. Indeed, some human performance enhancement drugs, such as caffeine, are widely used across the US military today. Existing technologies have demonstrated the ability to improve individual physical and cognitive performance above baseline levels and in key areas central to the military competition: strength, focus, attention, learning, and fatigue resistance. Moreover, many of these technologies are already being used in civilian, licit or illicit contexts."*

Cognitive Enhancement

Cognitive enhancement is one of the most sought-after and difficult human enhancement technologies. Improving cognitive capabilities relies on enhancing our understanding of the brain's structure and associated cognitive processes. Innovations in *Data*, sensors, and developing brain-machine interfaces are underlying technologies critical in driving this rapidly evolving area. This is expected to continue over the next 20 years. In addition, new developments in brain science will be harnessed to improve cognitive performance and neurological and psychiatric care within military medicine and generate new techniques and technologies for treating brain injury, neurodegenerative diseases, and certain psychiatric conditions, including those likely to affect the armed forces, such as post-traumatic stress disorder.

A significant body of early research focuses on novel methods of cognitive enhancement. This entails cognitive augmentation and focuses on methods of recovery and replacement. Such novel neuroscientific techniques and technologies may, in the future, better enable the treatment and resilience of NATO personnel or optimise their performance, particularly for increasingly arduous and fast-paced operations.

Leveraging Systems Biology advances, predictive network models are emerging as an area of focus that will provide tools to quantify the structure and predict system function. In the future, this could enable the prediction of cognitive function, disease onset or progression, behavioural responses to health messaging, or optimal strategies for early intervention. As these new models of brain functioning emerge, new techniques have been developed to monitor and manipulate neural activity. As these technologies advance, there is hope for new direct interventions to treat neurological diseases and functions, improving post-combat medical care.

Innovations in *Data*, sensors and brain-machine interfaces are underlying vital technologies driving this rapidly evolving area. One specific area of research is cognitive recovery from trauma and augmentation. Innovation and applications are expected to be rapid but constrained by necessary testing protocols and ELM considerations.

Other methods of human augmentation include the development of new physiological and pharmacological cognitive (PCE) enhancements, with attendant reproducibility, medical, ethical, legal and policy considerations (e.g. [263, 264]). Direct peripheral nerve stimulation and other non-invasive methods may also be used to increase synaptic plasticity for improved cognitive performance and learning [170], supporting rapid and practical training of military personnel in complex multi-faceted tasks.

Mixed reality is another example of human augmentation, blending the real and virtual worlds to create new digital or manufactured realities where physical and digital objects co-exist and interact in real-time. Applications include heads-up or head-mounted displays for pilots and soldiers for real-time situational awareness, digital cockpits/windows, realistic training environments or providing hands-free job performance aids. Augmented Reality and Virtual Reality are subsets of Mixed Reality. Computer simulation models are often used to deliver these experiences. Recent attempts at large-scale commercial product releases for head-worn, see-through, virtual displays have reopened interest in using head or body-worn virtual displays.

Reference [256] notes that these technologies will rapidly mature over the next 20 years and be primarily driven by the commercial market. This bio-economy is already at the earliest stages of development (e.g. Google Glasses [265]), while the pharmaceutical industry is one of the world's most significant, contributing over 200M euros to the EU economy alone.

In the near term, significant changes in advancing heads-up displays over the past five years will be refined to offer the following:

- Improvements in the power efficiency of micro-displays;
- Advancements in optical fabrication techniques for free-form optical surfaces; and
- Integration and proliferation of smartphones and wireless data links.

Social Enhancement

Social networks and their importance in modern societies are effectively self-evident. Unfortunately, much of the research and development in this area is driven by commercial considerations. However, methods for understanding, modelling, and simulating the dynamics of such systems are becoming increasingly sophisticated and yielding a better understanding of human social behaviour. This sophistication is necessary to predict the emergent properties of such systems better and target social effects, such as disinformation and cognitive and hybrid warfare campaigns. A second research trend is using "virtual reality" to augment and enhance social interaction. These areas are expected to grow in importance in civil and military applications. Developments in this area should be expected to be closely linked with human-machine teaming.

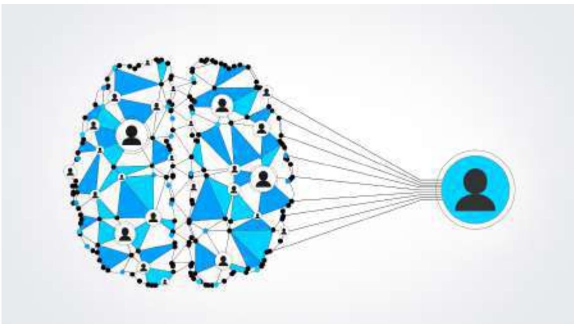


Figure C.3: *Social Augmentation and Enhancement.*

Research and development of interest will be focused on understanding, modelling, and simulating the dynamics of such systems to predict emergent network properties in the context of disinformation and cognitive warfare campaigns. Virtual reality social reality will continue to expand and deepen.

The social domain is an essential element of human existence, and technology has provided social enhancement technologies in the form of social networks and media. A social network is a network of social interactions and personal relations. Social media is a set of mediums that can be used for social networking. Social media and networks have helped reshape the social, economic and political world over the last 15 years [266, 267], with over 3.5 billion daily users (45% of the world's population). Social media has been widely embraced, gaining tremendous power to affect the perceptions and behaviours of individuals and societies. As such, it has become critical for the defence, security and safety of the Alliance, and it is the prime human terrain for operations in the cyber and information domains. The amount and variety of social media (whether text, audio, photographic or video in nature) is immense and growing at an astounding rate.

Although social media is a product of the Internet era and most notably the 21st Century, the research on social networks predates the internet by a wide margin. One of the first major social networking studies in the 20th Century resulted in the *Six Degrees of Separation (SDS) Theory*, first proposed by Frigyes Karinthy in 1929. In 2008, after the advent of the internet, Microsoft conducted a study demonstrating that the average e-mail chain length was 6.6 hops. However, in 2016, researchers at Facebook reported that social networking had reduced the chain length to three and a half degrees of separation. As such, social media and social networks may be best understood as a means for human social augmentation, and they have been highly successful at it.

The growth of the global information network presents significant challenges in understanding dynamic information flows within the network and the associated velocity, variety and veracity challenges.

Understanding the dynamics and spread of information within social networks, whether by individuals, groups, societies or states, is essential to our understanding of weaponised information and the role this plays in hybrid warfare [268]. Understanding how this dynamic may be exploited is of considerable commercial (e.g. Google, Facebook, Amazon, etc.) and military interest [170, 269].

Physical Performance

Augmenting physical performance, be this strength, endurance, pain tolerance or fatigue tolerance, has been the objective of militaries for a millennium. R&D will enable significant new approaches to man-machine augmentation and the potential of new pharmaceuticals. New computational methods will predict and optimise drug activity profiles to develop pharmacological interventions capable of modulating multiple targets within the body's biological systems.

The broad deployment of exoskeletons in commercial sectors will remain quite limited for the short term due to their high cost (more than $25,000 per suit). Nevertheless, *"it's clear that the era of the exoskeleton has begun"* [270] in areas such as logistics (e.g. warehouses), construction and manufacturing (e.g. cars and aviation) to ease worker burden, improve efficiency and reduce injuries. By 2025 the exoskeleton market will be 1.8 billion USD, up from 68 million USD in 2014 [271]. In addition, the US Army and others are moving forward quickly with development and exploring the operational effectiveness of exoskeletons in theatre [272, 273].

Human-Machine Symbiosis

Means for augmenting human performance through mechanical or electronic means have been accelerated through increased use of AI/ML and human-machine interfaces. Areas of particular interest are substituting biological, cognitive functions, computer vision and augmented reality.

Means for augmenting human performance through mechanical or electronic means have been accelerated through increased use of AI/ML and human-machine interfaces. Areas of particular interest are the substitution of biological, cognitive functions, computer vision and augmented reality. The advances in this area are underpinned by AI and Machine Learning (AI/ML) methods combined with new recording and manipulation techniques that will allow researchers to study the integration of multiple sensor inputs and their transformation into behavioural output. SWaP-C considerations will drive the use and ultimate capability development of sensory and motor augmentation, such as virtual reality contact lenses and exoskeletons.

MILITARY IMPLICATIONS

BLUE

There are many potential defence applications of these scientific and technological developments. The impacts of biotechnology are vast and will become increasingly widespread as the science matures. Regarding NATO, biotechnologies manifest in 4 primary spheres of influence, military systems and logistics, information competition, the human/warfighter and the environment.

Enable

Biomanufacturing utilises organisms, components thereof, or biological processes to produce commercially important molecules and products in the agricultural, food, energy, material, and pharmaceutical industries. Biotechnology provides next-generation materials previously unattainable through traditional industrial chemistries, and biological manufacturing often produces fewer toxic by-products than traditional chemistries, providing cleaner chemical sourcing. However, while biomanufacturing advances rapidly, the science continues to outstrip regulatory frameworks. This is a challenge for the setting of norms and standards.

For example, biotechnology is increasingly replacing oil refining to make commodity chemicals, including energetics and propellants. It has been reported that two-thirds of the world's most used chemicals could be synthesised from renewable raw materials, reducing reliance on fossil fuels. Microbes grown in fermentation vats are already being trained to produce these chemicals, and synthetic biology allows for making previously unattainable chemicals. Biomanufacturing is attractive to industry because of the low capital expenditure to build a facility, and biofoundries can fairly easily switch from one product to another with little investment aside from seed stock since the same equipment can be used to produce a variety of chemicals even though they are sourced from different organisms.

Another area that is increasingly influenced by biologics is adhesives production. Organisms have perfected the ability to adhere to various surfaces in various environments. Scientists are taking their cues from these secretions and mimicking the compounds, producing sometimes stronger and less caustic adhesives for multiple purposes.

Prepare

Using biomarkers (phenotypic and genetic) for predictive diagnostics will enable pre-deployment identification of medical issues or weaknesses (e.g. muscular-skeletal, psychological, immunological, physiological or nutritional). Improved diagnosis and novel countermeasures will increase occupational readiness and effectiveness for forces in high-risk, high-threat environments. In addition, human state monitoring in real-time to near real-time will optimise individual and team performance.

Their success in marine environments and the number of bacterial cells in the sea allow them to colonise nearly all artificial surfaces in contact with seawater. As a result, the costs to maritime transport, aquaculture, oil and gas industries, desalination plants and other industries are high, which has led to the development of various strategies to prevent biofilm formation and clean infected surfaces.

Engage

Rapid advances in material, computer and human sciences, as well as convergence between these fields, are setting the stage to enhance human capabilities and significantly push the human performance frontiers. Optimising the performance of each individual, be it in the cognitive, physical or resilience domains, in addition to improving team cohesiveness and effectiveness, will enable Alliance forces to make better decisions faster and produce actions better tuned to the situation's needs. Current and future advances in physiological and psychological state monitoring will maximise overall human performance and readiness through specific user group algorithm applications. Benefits include better leadership assessment of force status, increased training program adaptation and effectiveness through real-time performance metrics, and increased health and safety monitoring and injury protection. Bioinformatics, biosensors and increased personalised and virtualised training will improve training effectiveness. Muscular-skeletal augmentation (e.g. exoskeletons) will increase load-carrying capacity during operations, reduce debilitating injuries and increase combat performance.

Virtual reality and, ultimately, neural interfaces will support significant improvements in situational awareness and operations of autonomous systems. Heads-up displays, currently used in aviation and to a lesser extent in automobiles, could also find uses in dismounted soldier systems. Heads-up, eyes-out targeting could be achieved by overlaying targeting symbols on top of real-world targets. Mixed reality could be used to assist planners and mission rehearsal. Immersive visualisation of rapidly generated accurate 3D representations of the physical domain (terrain + buildings + infrastructure) from open source and military data and observations could provide staff with a realistic feel for the landscape before being exposed to it in real life. Mixed Reality setups are already used to provide practical, cost-effective training environments. Advances in computer networking, processing and analytics will see such configurations used on the battlefield and in expensive labs. Neurological interfaces will increase response times, situational awareness and the effectiveness of man-machine teaming.

Protect

Use of biomarkers, biosensors (in vivo & in vitro) [274] and microarrays (microfluidic devices integrating computing chips with living cells and tissue) will allow rapid (pre-symptomatic) diagnosis and response to synthetic or natural pathogens, chemicals, as well as real-time monitoring of treatment options. In addition, the use of biomarkers, novel pharmaceuticals, gene therapy and bio-engineering (e.g. robotics, prosthesis, neural interfaces, etc.) will dramatically increase the effectiveness of combat casualty care and rehabilitation, especially in such areas as post-traumatic stress disorder (PTSD), environmental exposure and mild-traumatic brain injury (mTBI).

Bacteria have already been used to detect improvised explosive devices, and this application could be extended [275].

Novel synthetic biological and chemical agents pose a new threat to Allies and will require constant efforts to ensure adequate defence.

Sustain

Biotechnologies act upon both organic organisms and inorganic objects and will increasingly impact military platforms, equipment and tools both for the benefit and potentially with negative consequences. In the future, these technologies will be employed in austere environments, decreasing logistics chains, reducing deployment footprints and saving money.

Biological organisms have produced and stored energy since they evolved. These processes can be harnessed, allowing biotechnologies to produce and harvest energy and provide long-term energy supplies. Microbial fuel cells offer living, rechargeable power generation and energy storage for low and ultra-low devices. Carbon fixation platforms provide a sustainable and independent mobile energy harvesting mechanism. Furthermore, biofuels are becoming increasingly sophisticated and integrated into military operations reducing the environmental impact of operating military machinery.

On an individual level, wearable biomedical systems that can monitor soldier health continuously could provide knowledge of the inception and progress of injury over time. Knowledge of the health status of soldiers on the battlefield could greatly benefit BLUE forces in providing essential information needed for force condition status assessment. Additionally, forces leveraging bioinformatics, sensors and enhancement technologies should be able to operate in smaller groups, which has implications on affordability (e.g. a smaller number of soldiers, sailors, or aviators can achieve similar results).

Bioprinting will allow just-in-time logistics and troop sustainment in austere environments.

Biomanufacturing could significantly reduce the number of people and equipment needed to build air base facilities. The final prototype used local dirt instead of concrete mix to create a hardened surface. In a future conflict, adversaries could be attacked by US forces operating out of previously unknown airfields, all thanks to tiny creatures invisible to the human eye.

Inform

Social media supports military activities in six key ways [269]: intelligence collection; (geo-) targeting; cyber operations; command and control; defence; and psychological warfare (inform and influence). Fusing social media (as part of OSINT (open-source intelligence)) with other data and integrating social network operations into broader operational and strategic actions will be a critical success factor in countering hybrid and memetic warfare operations.

Biologics may be able to detect and indicate personnel movements.

RED

The benefits of RED are similar to those available to BLUE. BHET threats will increase driven, in no small measure, by democratising associated technologies. Peers, or near-peer strategic competitors do not share significant Alliance ethical, legal, societal, moral, and policy norms. However, their use by security threats (both criminal and otherwise) or the use of non-sanctioned enhancements by individuals will be more problematic. With globalisation and the increased pace of scientific discoveries, there is a high likelihood that an adversary force will have access to the knowledge necessary to create similar capabilities. The implications on the battlefield are that RED would have a significant performance advantage if such a force is not constrained by the same ethical considerations in implementing these new technologies.

In particular:

1. **Synthetic Biology**: New pathogens, novel biological agents or chemical agents, with explicitly engineered and targeted effects (e.g. increased virulence, physical, neurological or physiological impact, genetic susceptibility, etc.), will potentially increase casualties, reduce combat effectiveness and present a strategic challenge to Alliance societies as a whole. In addition, the effect of unknown biological agents will challenge the capacity of medical and logistics systems to cope, while countermeasures themselves may present significant health and safety challenges.

2. **Designer Pharmaceuticals**: Criminal and non-state actors will increasingly have the ability to develop low-cost targeted pharmacological agents. These may be used explicitly to disrupt Alliance operations or destabilise alliance societies through targeted psycho-social effects.

3. **Super-Soldiers**: BHET will enable pharmacologically, neurologically and physiologically enhanced opponents. Combined with more effective partnering with autonomous and semi-autonomous systems, these will significantly challenge Alliance forces, force structure and effectiveness.

Interoperability

Alliance interoperability will be challenged by differing legal, policy, training, operational effectiveness and ethical standards amongst the nations driven by BHET. Development of standards for personal biosensors, handling bio-data, sharing medical countermeasures, man-machine interfaces (including neurological) and bio-mechanical systems will be critical enablers of effective Alliance BHET-enabled operations and capabilities.

S&T Development

State of Development

Data

Bioinformatics and Biosensors: The collection, classification, storage, retrieval and analysis of biological and biochemical data leveraging new sensor materials, AI and BDAA. The research will explore new biosensors (including bio-engineered) and bio-data collection methods for detecting biomarkers, as well as the processing and exploitation of massive amounts of personalised, cohort, ISR and environmental data. In addition to increased situational awareness, this will support the development of increasingly sophisticated and predictive models and simulations supporting clinical interventions, personalised medicine, individualised training, and assessment of natural or artificial biological threats [170].

AI

Bioinformatics supplies large amounts of data that can be utilized as training data sets. As AI technology improves, AI will be increasingly used for human health diagnostics and designing synthetic biological organisms. Increased understanding of neural networks will improve the learning algorithms serving as the basis for AI architecture.

RAS

RAS design is increasingly inspired by living organisms, which will allow possible long term energy supply and enhanced operation and maneuverability in a variety of environments

Space

Biotechnology and Human Enhancement Technologies will improve human survivability and functionality in space, allowing the human body to better survive long term space exploration, providing new means for terraforming new celestial systems, and ultimately allowing for human colonization in space. Along with this though, space travelers must be conscious of the effects of stow-away, “invasive” species, which could adversely affect alien environments and human attempts to colonize them.

Quantum

The emerging field of quantum biology is slowly gaining momentum and can be applied to a variety of theoretical contexts. For instance, some hypothesize that natural organisms use quantum coherences to direct energy transfer [276].

BHET

Medical Countermeasures and Technologies: The development of new diagnostics, therapeutics and vaccines (employing bioinformatics, genetic engineering and biosensors) to support predictive diagnostics, CBR threat identification, modelling and treatments. Combat casualty care will apply for advances in molecular and cellular biology, AI, bioinformatics, and novel materials to improve the rapid identification and treatment of tissue damage and infection.

Human Augmentation (Physiological & Cognitive): The use of genetic modifications, pharmacological agents, electro-mechanical devices, and neurological interfaces to increase human physiological and neurological performance beyond normal limits.

Human Augmentation (Social): Increased computational and modelling capabilities to understand information flow within complex social networks (social media). Developing novel quantitative methods will be essential if a deeper understanding of information network dynamics is to be advanced and countermeasures designed in hybrid warfare.

Materials

Biologically inspired materials that mimic the properties of organisms that have evolved over millennia can provide enhanced properties compared to traditional materials, such as adhesives and new sources of anti-ballistic materials. Furthermore, bioprinting and biofoundries can produce materials when and where they are required, reducing logistics trains and with potentially fewer toxic byproducts than through traditional chemical means. **Biomanufacturing** and **Synthetic Biology** are expanding area of synergies between BHET and Materials. For instance, the deliberate design, engineering and creation of novel synthetic, or modified biological components, or systems. This includes the engineering of multicellular bio-sensor systems for surveillance and manufacturing.

Energy

Alternative fuels based on renewable organic molecules have already been incorporated in military operations within several nations. Additionally, in the future, it may be possible to harness the metabolic pathways of various organisms for a variety of military operational needs, from fueling autonomous vehicles to powering remote operating bases.

E&EM

Genetic engineering and synthetic biology are enabling a new class of living organisms to provide sensing capabilities that are either integrated in a biocomputing framework or in place of both active and passive sensor systems.

STO Activities

Several STO Scientific and Technical Committees have produced significant research on BHET technologies. All panels have ongoing activities on several topics aligned with these technologies. The following is a sample of ongoing activities:

- HFM-308 RTG: Optimising Human Performance in NATO SOF Personnel Through Evidence-Based Mental Performance Programming
- HFM-310 RTG: Human Performance and Medical Treatment and Support During Cold weather Operations
- HFM-325 RTG: Performance Nutrition for Fresh Feeding during Military Training and Operations
- HFM-330 RTG: Human Systems Integration for Meaningful Human Control over AI-based systems
- HFM-331 RTG: Biomedical Bases of Mental Fatigue and Military Fatigue Countermeasures
- HFM-341 RTG: Validation of Modeling and Sim-

ulation Methodologies for Human Lethality, Injury and Impairment from Blast-Related Threats

- HFM-344 RTG: Human Impact Exposure onboard High-Speed boats
- HFM-349 RSY: Human Performance and Medical Treatment and Support During Cold Weather Operations
- HFM-358 RTG: Microbiome Applications in Human Health and Performance
- HFM-359 RTG: Ionizing Radiation Bioeffects and Countermeasures
- HFM-365 RTG: Human Capability & Survivability Enhancement: Augmenting people to deliver an enhanced and more resilient capability for defence
- HFM-367-T-RTG RTG: Pre-Symptomatic Detection of Biological Exposures
- HFM-ET-192 ET: Blast Exposure Monitoring in Military Training and Operations (BEMMTO)
- HFM-ET-193 ET: Skills and chill pills: Navigating the cyber-social information environment
- HFM-ET-195 ET: Pre-Symptomatic Detection of Biological Exposures
- HFM-ET-196 ET: Enhanced Physical Protection and Hazard Management in CBRN Defence
- HFM-ET-201 ET: Human Security
- HFM-ET-205 ET: Digital mental performance training for optimal human function
- HFM-ET-206 ET: Biomanufacturing of National Security Materials
- HFM-317 LTSS: Solutions for Combat Casualty Care
- HFM-MSG-354 RTG: Study, Design, Building and Deployment of a CBRN XR Training Platform
- IST-177 (IWA) RTG: Social Media Exploitation for Operations in the Information Environment
- LS-239MAIL: Chemical and Biological Defence
- LS-241MAIL: Pathological Aspects and Associated Biodynamics in Aircraft Accident Investigation
- MSG-173 RTG: Simulation for Training and Operation Group – Next Generation (STOG-NG)
- MSG-174 RTG: Urban Combat Advanced Training Technology Live Simulation Standards (UCATT-LSS) - 2
- MSG-180 RTG: Implementation of Live Virtual Constructive – Training (LVC-T) in the Maritime Domain
- MSG-198 ST: Composable Human Behaviour Representation in Constructive Simulation Systems
- MSG-204 ST: NMSG support to Distributed Synthetic Training (DST) A2CD2 efforts
- MSG-206 RTG: Common Framework for the assessment of XR technologies for use in Training and Education
- MSG-208 RSY: MSG/MSCO Support to International Training & Education Conferences IT2EC, I/ITSEC and CA2X2 Forum 2023
- SET-249 RTG: Laser Eye Dazzle Threat Evaluation and Impact on Human Performance
- SET-HFM-ET-126 ET: Nanopore Sequencing for Biological Identification
- SET-HFM-ET-130 ET: Existence and Detection of Signal-induced Human Performance Degradation (HPD)

Scientometric Analysis

Keywords associated with Biotechnology and Human Enhancement Technologies (BHET) as derived from STEAM analysis are shown in Figure C.4.

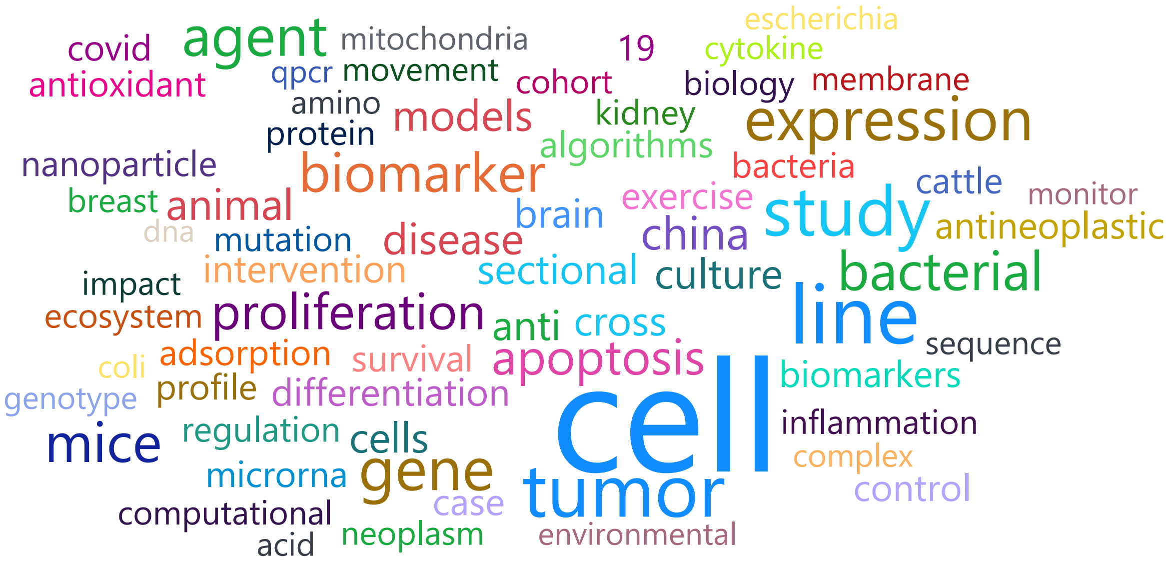


Figure C.4: STEAM - Bio and Human Enhancement Technologies - Keywords

Survey Results

The following table presents the assessed potential impact, state and rate of development and identifies areas for focused research.

Table C.1: Biological and Human Enhancement Technologies (BHET) 2023 - 2043.

EDT	Technology Focus Areas	Impact	TRL	Horizon
BHET	Bio-engineering & Genetics	High	5-6	2030-2035
	Bio-informatics	High	7-8	2025-2030
	Bio-manufacturing	High	3-4	2030-2035
	Bio-sensors & Bio-electronics	High	3-4	2030-2035
	Cognitive Enhancement	Revolutionary	3-4	2035 or (+)
	Human-Machine Symbiosis	Revolutionary	3-4	2035 or (+)
	Physical Enhancement	High	5-6	2030-2035
	Social Enhancement	High	5-6	2030-2035

Conjecture Card: Bio and Human Enhancement Technologies

A. Super Sensings  Enhance human senses and cognitive abilities to super-human levels to increase the speed of learning/comprehension and reduce reaction times.	**B. Body Self-Repair**  Heal wounds, injuries or illnesses using DNA restructuring or synthetic biology solutions (e.g. artificially grown body parts).	**C. Bio-Databases**  Store or process massive amounts of data in living organisms.
D. Human-Machine  Mechanically augment the human body with an exoskeleton or internal mechanical parts to gain super strength, balance and speed.	**E. Chem or Bio Analysis**  Instantly analyse and identify chemical or biological substances remotely or using hand-carried or unmanned systems.	**F. Health Monitoring**  Continuously monitor the health and well-being of entire populations at the individual level, activating drugs, hormones, or genes on demand.
G. Train in Reality  Deploy realistic virtual or augmented reality training environments to prepare soldiers in real-time for mission tasks.	**H. Psychotic Effects**  Remotely induce mass hysteria or hallucinations in groups or individuals.	**I. Genetic Targeting**  Design and develop targeted pathogens, antidotes or neutralising CBRN agents from materials and knowledge available at low cost and to everyone.
J. Grow an Airfield  Using bio-concrete, grow an entire stealth airfield and infrastructure in austere conditions with RED forces unaware.	**K. Living Sensors**  Design and deploy living bacterial sensors for mine detection, intrusion monitoring and early detection of CBRN threats.	**L. Super Soldiers**  Genetically modify and create super soldiers for maximum efficiency on the battlefield.

D. Data

Data - The DIKW Pyramid

"**Data** is not information, **information** is not knowledge, **knowledge** is not understanding, **understanding** is not **wisdom**." - *Clifford Stoll* [277]

Definition

Big Data, Advanced Analytics and Information Communication Technologies (or *Data*)

Data describes Big Data (raw digital data) that presents significant volume, velocity, variety, veracity and visualisation challenges. Increased digitalisation, a proliferation of new sensors, new communication modes, the internet-of-things and the virtualisation of socio-cognitive spaces (e.g. social media) have contributed significantly to the development of Big Data. *Advanced (Data) Analytics* describes advanced analytical methods for making sense of and visualising large volumes of such information. These techniques span various approaches drawn from research areas across the data and decision sciences, including artificial intelligence, optimisation, modelling & simulation (M&S), human factors engineering and operational research. Two additional aspects are essential in considering the big data challenge: *Information and Communication Technologies*, and sensors and sensing. This system-of-systems is necessary for an effective multi-domain C4ISR framework, reflecting the collection, processing, exploitation and dissemination of information supporting decision-making and C2.

Keywords

Big Data · Optimisation · Analytics · 5G · 6G · Operations Research · Decision Science · Data Science · AI · Human Factors · Predictive Analytics · Business Analytics · Business Intelligence · Data Lakes · Data Mesh · Data Fabrics · Data Lakeshore · Wireless · Data Architectures · ICT (Information and Communication Technology) · Supercomputers · Wireless

Overview

Context

Big Data Challenges

Modern technological development is driven along four mutually reinforcing lines of advance, resulting in technologies that are increasingly (1) Intelligent; (2) Interconnected; (3) Decentralised, and (4) Digital [2]. The common link between these four trends is the essential nature of *Data* and the networks, systems, computers, communications, and interfaces that collect, analyse, and ultimately store it. Within EDTs, *Data* may be considered one of the core enabling technologies. This EDT was originally conceived of as *Big Data and Advanced Analytics (BDAA)*, defined as *a term used to describe the large amount of data in the networked, digitised, sensor-laden, information-driven world* [278]. Given this definition, using *Data* as an EDT from a NATO perspective may be more productively described as "*Data and Information Communication Technologies*, thereby covering aspects such as analytics, sensors, computers, and networks. We shall use this broader definition when speaking of *Data* in the context of this appendix.

The digital backbone of modern technologies consists of the networking and services provided to deal with data challenges. The term Big Data or simply *Data* is rather vague [279]. Nevertheless, Table D.1 outlines a proper semantic structure for big data [278] as does [13] in a larger S&T context. In addition, [280] provides a useful set of definitions and taxonomy. *Data* and its constituent technologies form the digital glue that brings together and enables all other EDTs and the fourth industrial revolution.

Table D.1: *The Semantics of Big Data [278]*

NAME	SHORT MEANING	BIG DATA CONTEXT
Volume	Size of data	Voluminosity, Vacuum and Vitality
Velocity	Speed	Transfer rate, and Growth rate of data
Variety	Numerous types of data	Structured, unstructured and semi-structured
Veracity	Accuracy and truthfulness	Accuracy of data
Validity	Cogency	Correct data
Value	Worth	Given worth to the raw data
Virtual	Nearly actual	Managing large number of data
Visualisation	To be shown	Logically display the large-set data
Variability	Change	Change due to time and intention
Vendee	Client management	Client management and fulfilling the client requirement
Vase	Big Data Foundation	IoT, Cloud Computing, etc.
Complexity	Time and Space requirement	Computational Performance

Data is an enabler for other technology areas, with its roots in mathematics, statistics, information science, engineering, and human factors. Our world of experience has become increasingly digital and virtual in nature (Figure D.1). *Data* in and of itself has become a powerful yet often invisible agent of change [281]. New developments span a growing range of research areas and applications in defence and security. Consequently, NATO takes *Data* development seriously and has responded by developing a Data Exploitation Framework Strategic Plan [137, 282].

In 2006, the British entrepreneur and mathematician Clive Humby declared *"Data is the new oil"* [284]. Over the last 15 years, various authors (e.g. [285, 286, 287, 288, 289] to name a few) have opined that data has indeed become the *strategic resource* of the fourth industrial revolution. More significantly, new computational, analytical, and visualisation techniques have helped turn vast quantities of raw data into actionable information. This data and information availability has been an engine for global change, especially over the last twenty years. Thus, in many ways, it is more accurate to say that *information* is the strategic product and *data* is the strategic raw material for success in the modern geostrategic and social environment. Nothing foreseen over the next twenty years is expected to change this fundamental aspect of contemporary civilisation.

It is useful to take a moment to understand just how important data has become and the sheer volume involved [290, 291, 292, 291, 283]. To put this data problem in proper context, in 2022, the world created 94 ZB (10^{21}) of data, with 80 to 90% of that data unstructured. Furthermore, that number is expected to double every two years, rising to over 100,000 ZB annually by 2043 if this trend continues unchecked.

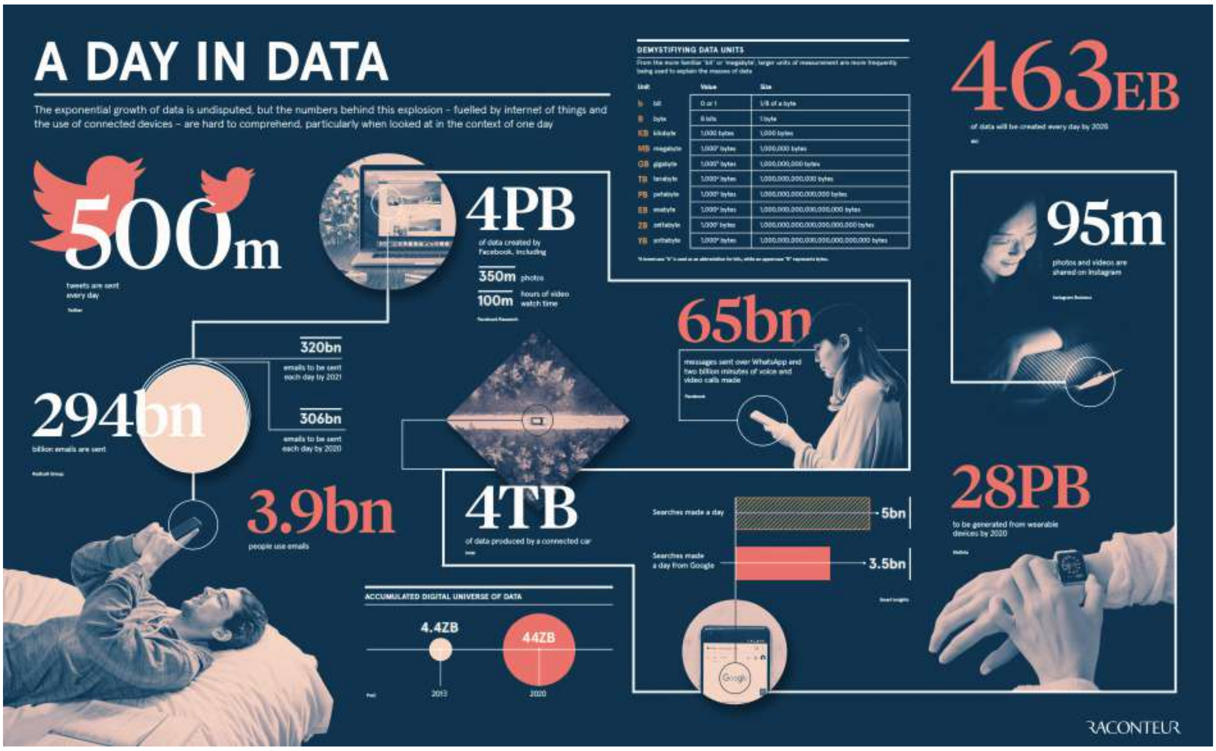


Figure D.1: *A Day in Data - 2019 CREDIT: [283]*

The amount of data collected daily is truly staggering. We live in a world approaching yottabytes (Table D.2) of data per year by 2043. In 2025, this works out to an expected 463 exabytes per day globally [293]. Indeed, the volume of data is increasing so much that in November of 2022, the SI table of data was extended from Yottabytes (10^{24}) to Ronnabytes (10^{27}) and Quettabytes (10^{30}) [294, 295, 296].

Table D.2: *SI (metric) Units for Data Storage*

Unit (SI)	Abbreviation	Value	Size	Context
bit	b	0 or 1	1/8 of a byte	
byte	B	8 bits	1 byte	a character in the alphabet
kilobyte	kB	10^3	1,000 bytes	a paragraph of text
megabyte	MB	10^6	1,000,000 bytes	a small novel
gigabyte	GB	10^9	1,000,000,000 bytes	a large personal library
terabyte	TB	10^{12}	1,000,000,000,000 bytes	one-tenth of all the printed text in the US Library of Congress
petabyte	PB	10^{15}	1,000,000,000,000,000 bytes	half the contents of all US academic research libraries
exabyte	EB	10^{18}	1,000,000,000,000,000,000 bytes	one fifth of all the words ever spoken on Earth
zettabyte	ZB	10^{21}	1,000,000,000,000,000,000,000 bytes	the grains of sand on all the world's beaches
yottabyte	YB	10^{24}	1,000,000,000,000,000,000,000,000 bytes	the stars in the observable universe or atoms in 100 elephants
ronnabyte	RB	10^{27}	1,000,000,000,000,000,000,000,000,000 bytes	The Earth weighs approximately 1 Ronnagram
quettabyte	QB	10^{30}	1,000,000,000,000,000,000,000,000,000,000 bytes	Jupiter weighs roughly one-third of a Quettagram

The digital universe dominates our reality. According to the World Economic Forum, 60% of the global GDP is digitised. Also, data (not in analogue form) created in 2021 and 2022 alone represents 90% of all data ever created by humanity. When the last technology trends report was written in 2020, the world's cloud data storage was 6800 EB (1000 EB makes a ZB). This volume is expected to grow to more than 200 ZB by 2025. All this data must be requested, collected, transmitted, processed, exploited, and stored, creating a growing demand for energy and analytical tools. The Internet alone generated 2 million tons of CO^2 per day (2022) [291]. This digital demand creates huge piles of waste products, including toxic e-waste. It is estimated that only 32% of the information available to businesses is leveraged in any form [297], and overall, only 0.5% of digital data is exploited [298].

Data sets of a magnitude and complexity that are difficult to handle logistically (a definition that it must be noted changes yearly) due to increasing *volume*, *velocity*, *variety*, *veracity* and *visualisation* issues will present significant technical, organisational and interoperability challenges. Distributed sensors,

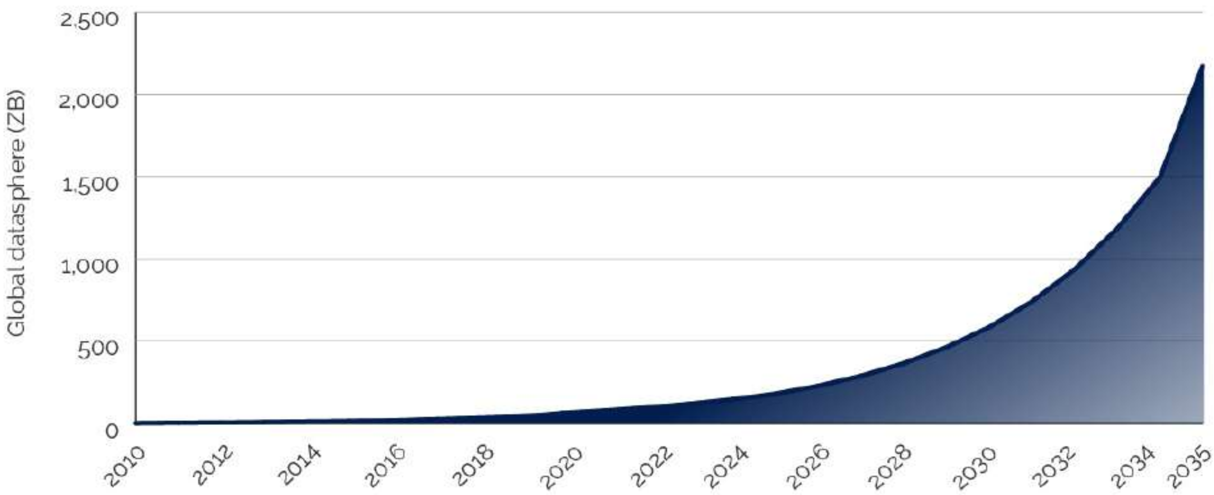
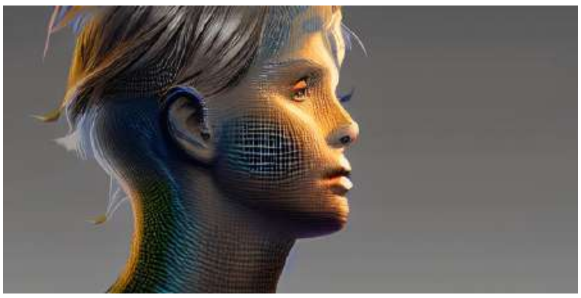


Figure D.2: *Annual Global Datasphere Forecasts 2010-2035 [299]*

autonomous systems, new communication technologies (e.g. 6G), new antenna developments, improved spectrum usage, increased use of space assets, virtual socio-cognitive spaces, digital twins, ever more power-efficient electronics, and the development of new and expanding analytical methods will increase our ability to *understand* the human, physical and information domains. *Data* is the enabling technology for all EDTs and is central to their exploitation for enhanced military capabilities. For example, AI requires high-quality curated training data to develop new algorithms and applications, placing even greater demands for more and better data, even as it helps us understand and utilise the data deluge.



Overstating data's importance in driving and enabling EDT development is difficult. Consequently, NATO must ensure that the digital backbone and analytical methods it will use in the upcoming years will be up to the task. AI is a critical complementary technology whose growth is a reaction to this data volume challenge as well as one that exploits the information opportunity. In turn, this combination of *Data* technologies has created a global network with characteristics of neural systems, a point noted originally by the media theorist Marshall McLuhan [300, 301].

As with any strategic resource, competition is fierce. Over the last decade, the epicentre of competition with Russia and the People's Republic of China (PRC) has been less about controlling the *means of production* and more about the *means of information production and dissemination*. More specifically, this competition centres on developing, controlling, exploiting and weaponising information, communication, computation, and sensor technologies [103]. Data, abundant and ubiquitous, has become cheap, while information has become invaluable. Controlling underlying Information and Communication Technologies (ICT) will enable exponential economic and scientific development, thriving societies, international cooperation and geostrategic power [103]. On the other hand, it will also allow techno-authoritarianism and a loss of privacy. As is already the case, these meta-technologies are opening up a wave of *"ABC"* developments centred on *"atoms, bits, and cells"* [103].

This information-dominated domain is challenging. Privacy, disinformation, technology standards, IP warfare, and malicious use of data challenge Alliance nations and enable techno-authoritarianism. As shown in Figure D.3, storing this information must keep pace with data growth [302]. However, it must also be noted that not all data is valuable. Data has a shelf life, compression and data reduction techniques allow a significant reduction of data volume and information generation condenses data into more usable forms [303].

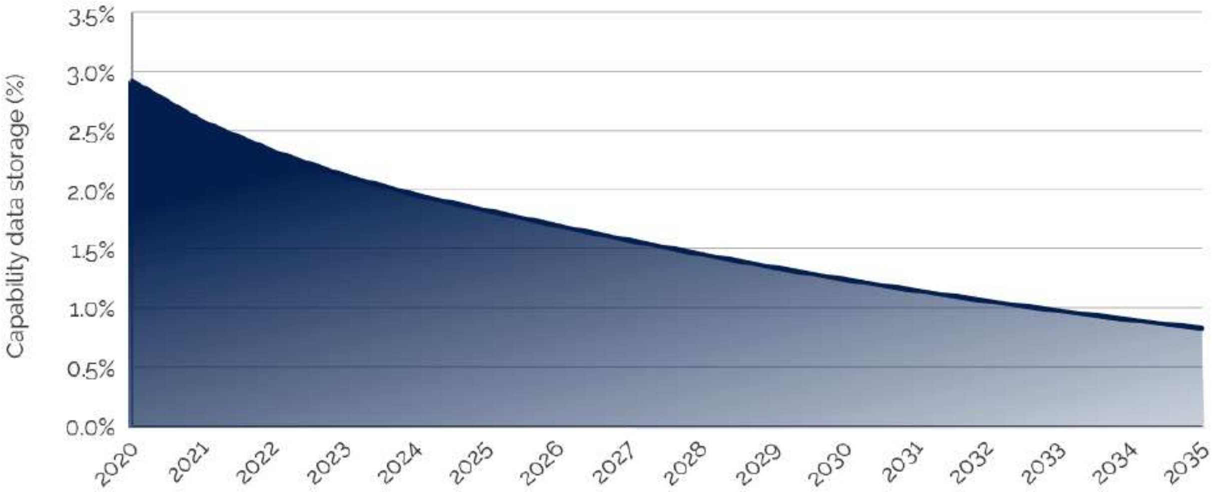


Figure D.3: *Global Data Storage [299]*

Military Context

For nearly seventy years, the world has been in a state of digitisation, digitalisation, informationalisation, and, more recently, intelligentization, itself a clearly stated objective of the PRC and People's Liberation Army (PLA) [304, 305, 306]. These, in turn, have led to military trends towards increased autonomy, precision warfare, expanded operational domains, and the rising importance of battle networks [2]. ICTs underlie these changes, providing the digital backbone for multi-domain operations. This growth in data will have a fundamentally disruptive effect on Alliance operations, capabilities, and technological development.

Developments in *Data* S&T are driven by *massive* commercial investments and publicly available training data sets and tools for algorithm development and testing [307, 308]. Many alliance nations have made significant *Data* investments in civilian and military domains. NATO will, therefore, be able to leverage these investments while extending, adapting and integrating them into NATO processes and operations. Continued investment in enabling capabilities, R&D collaboration and common standards and policies for data collection, curation and management will be necessary to ensure the successful integration of *Data* into the Alliance enterprise and operations. Potential legal, commercial, and IP issues may provide additional challenges to successfully using *Data* in a NATO context. Such challenges include introducing unanticipated vulnerabilities, limited configuration control and a need for explainability.

For NATO, improvements in *Data* technologies will enable increased operational efficiency, reduced costs, improved logistics, real-time monitoring of assets and predictive assessments of campaign plans. At the same time, it will generate significantly greater situational awareness at strategic, operational, tactical and enterprise levels. These applications will lead to a deeper and broader application of predictive analytics to support enhanced decision-making at all levels, a point recognised by other near-peer competitors [309]. It has the potential to create a knowledge and *decision advantage*, which will be a significant strategic disruptor across NATO's spectrum of capabilities. There is the potential to significantly impact NATO's kinetic and non-kinetic targeting effectiveness using cheap, widely distributed sensors (as part of the internet-of-things (IoT)), linked by new communication protocols (such as 6G), building on analyses and dissemination of critical information in real-time. Potential peer or near-peer adversaries will seek a similar technical edge, while asymmetric threat actors will exploit increasingly open and available data sources for targeted effect or disruption.

The commercial sector invests heavily in *Data* and associated sensor and ICT technologies. Over the next 20 years, it is expected this will continue, and commercial interests will lead in the overall development and application. The effectiveness of this investment underlies the current knowledge economy. There are no indications that this will change soon. Nevertheless, the unique needs of NATO military forces will require developing methods and standards for interoperability, sharing, collection, modelling & simulation, analysis, classification, curation, communication, and data management. Finally, it is not a given that more data and advanced algorithms will ultimately produce better decisions [310, 311, 312, 313]. Nevertheless, understanding the complex socio-cognitive-technical context around decision-making and the proper role and integration of *Data* in this context will be essential to developing a NATO decision advantage. The human sciences will be particularly important in guiding developments in this area.

Technological Context

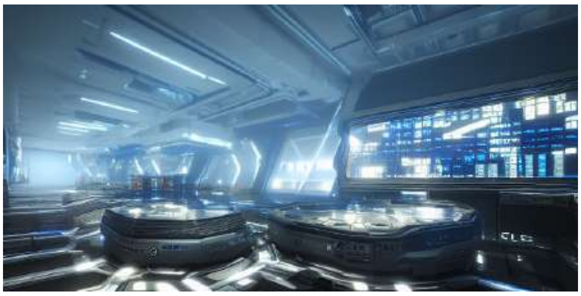
Data is a foundational technology; understanding its projected development is critical in understanding other EDTs. From a technology watch perspective, *Data* will be enabled by S&T advances in a variety of areas, which include: the exploitation of human signatures; modelling and simulation for social media; modular multi-sensor fusion engines; provision and discovery of M&S tools and services in the cloud; visual analytics; decision support and planning support with M&S in the battlefield; virtual mission areas; distributed ledger technologies (e.g. blockchain); cognitive sensing; compressive sensing; computational imaging; deep learning; electric-and magnetic-field sensing; photonic integrated circuits; sensing sources data fusion; swarm centric systems; and, wideband telecommunications.

Of all the EDTs *Data* is perhaps the most technologically broad, impactful and, at the same time, the most well-developed technological area. In no small measure, this is driven by the ongoing *informationalisation* and *inteligentization* of the geostrategic and military conflict space. There is broad recognition that the strategic resource for NATO and the nations is *information*, or as stated by John Naisbitt, *We are drowning in information, but starved for knowledge.* [314]. However, *Data* does not exist in a vacuum. The collection, processing, exploitation and dissemination technologies are essential to turn data into information, information into knowledge and knowledge into wisdom. As is readily apparent, the issue of big data, analysis, and ICT S&T is vast, dwarfing all other EDTs.

There are many ways to sub-divide big data problems; however, to be understood comprehensively, *Data* needs to be viewed as a series of technical challenges covering digital data collection, processing, exploitation and dissemination and analytical methods. Consequently, developments in *Data* are best considered along the following lines of effort: **(1)** Advanced Computing and Methods; **(2)** Novel Applications and Decision Making; **(3)** Distributed Leger Technologies; **(4)** Advanced Networks; **(5)** Sensors; **(6)** Storage; and **(7)** Cyber. These are discussed in more depth in the sections below.

Advanced Computing and Methods

Interest in *Data* is a direct outgrowth of our increasingly digital and virtual world and the subsequent need to make sense of the resulting information deluge. In particular, *analytics* is the process of generating understanding (e.g. through mathematical analysis and visualisation) and providing insights into current system states (*descriptive*) or future system states (*predictive*). The analyst often faces data with significant volume, velocity, variety, veracity or visualisation challenges. Vast amounts of data available throughout the future physical, human or information battle spaces will enable analytics to deliver insights and predictions, provide real-time decision support, and highlight early indicators of success and warnings of crises. Increased use of predictive analytics and M&S will enable decision-makers to exceed their cognitive limits while improving consideration, inter-dependencies, intra-transparencies, and temporal dynamics [315, 316]. Ultimately, this will allow decision-makers to understand their decision's potential impact better and adjust plans accordingly. Many aspects of *Data* are technically well-developed as it has been an area of R&D for over 70 years. While it is and will continue to be highly disruptive, some have questioned whether it should truly be considered an emergent technology, as it may be more productively considered as a *a megatrend that touches so many aspects of our interactions with computers–from the Internet of Things and content analytics to cloud computing and virtual reality* [317].



Developments in applied mathematics and the information sciences continue to yield new approaches to optimisation, statistics, modelling & simulation, management of uncertainty, and ways of addressing complexity and chaos. Some methods explore foundational approaches to improving the modelling and simulation of complex and complicated systems. Other areas of note are developing new statistical and analytical methods to assess data integrity and sparse data. These methods are empowered by advanced computational methods such as multi-part computation (*"analytics to the edge"*), new probabilistic programming languages, and accelerating advances in quantum computing. Finally, emergent results are coming to light in modelling and simulation, especially around data-driven models where empirical models of natural, complex processes and phenomena use libraries of data modelling primitives and human-model interfaces. Such developments are expected to continue over the next 20 years. To support this analytical need, new approaches, especially new computational paradigms, such as quantum computing, novel mathematical methods and developments in traditional supercomputers, will be essential, [318, 319, 320]. Concerning conventional supercomputers, biomimetic approaches such as neuromorphic supercomputers hold promise to increase supercomputer processing capabilities significantly [321, 322, 323, 324, 325]. New methods will also impact operational decision-making using new computing and data paradigms such as edge, fog, transparent, mobile, and dispersed computing. Competition for new supercomputers is currently and will continue to be an area of considerable competition [318, 326, 319, 320, 324, 327].

Over the next 20 years, data volume will continue to grow as the number of handheld and internet-connected devices grows exponentially and the IoT becomes a reality. In 2023, spending is expected to grow to 1.1 trillion USD globally, continuing the increased growth rate year-over-year [328]. By 2030, 500 billion items are expected to be interconnected [329]. The sheer volume of data that this will create is difficult to comprehend. The associated legal, policy and privacy considerations are decidedly non-trivial. Better tools for analyses (without the analyst) will need to emerge to deal with this deluge. Companies will grow the trend of becoming increasingly data-driven and willing to apply analytics-derived insights to critical business operations. Organisations will struggle with data privacy, security and governance issues.

Analytics and advanced computational techniques for data processing and fusion will improve sensor ranges and provide richer contextual information than is currently possible. Artificial Intelligence, specifically machine learning, is showing considerable promise in many areas, processing large volumes of seemly disparate, disorganised, and ostensibly unrelated information. These predictive, correlative models are valuable tools for detecting intent and predicting possible future actions and events. The utility of these models and deep learning techniques will increase as data-driven learning methods mature and the underlying data grows almost without bounds. That said, it has been estimated that 85% of all AI projects in business ultimately fail [330, 331, 332, 333].

Visualisation techniques are critical enablers in assessing social media data and supporting decision-making. The civilian market uses visual analytics extensively for marketing purposes, with estimates that this market was worth \$6.5 billion in 2021 and is projected to reach \$ 28.9 billion by 2031 [334]. In addition, this technology may be partly transferable to the defence and security domains.

Novel mathematical, computational, and human-factors approaches to analysing complex and complicated military socio-technical systems-of-systems (e.g. operational command), including fusion of noisy and uncertain data and operational decision-making. This includes modelling and simulating complex multi-scale physical, information and engineering systems. Development of data-driven discovery models

Table D.3: Analytics. CREDIT [335]

Types of Analytics	Characteristics	Examples
Operational Analysis	Complex analytic queries Performed on the fly as part of operational business processes Concurrent high data volume of operational transactions Real-time data fusion	Real-fraud detection, ad serving, high-frequency trading Processing ISR sensor data
Deep Analytics	Typically multi-sourced Non-operational transaction data Complex data mining and predictive analytics Real-time or near real-time response Uses map reduce-type framework, columnar databases, and in-memory analysis	Gaining insight from collected smart utility meter data Targeting
Time Series Analytics	Analytics with the concept of a transaction: an element that has a time, a numerical value(s), and metadata	Algorithmic trading Logistics analysis
Insight Intelligence Analytics	Analysis over a vast complex and diverse set of structured and unstructured information	Intelligence analysis

[170] will be an essential aspect of this research as human engagement in developing predictive models is a significant limiting factor. In addition, new distributed computational architectures (edge computing) and search and assessment technologies will be necessary to discover, organise and present multi-domain content [170].

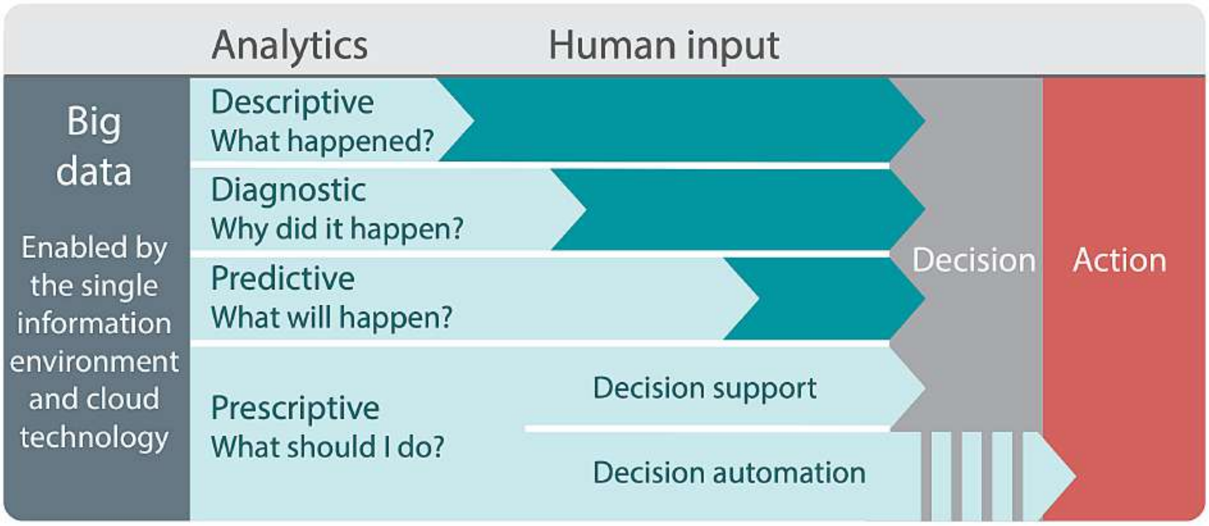


Figure D.4: Types of Analytic Capabilities [336]

Over the last 70 years, new methods to handle big data's increasing volume, velocity and veracity challenges and the development of new analytic, statistical or computational methods have impacted economies, policies, and strategies profoundly [337, 338, 339, 340, 341]. Areas of specific interest are:

- **Analytical Methods**: Applied mathematics continues to develop with optimisation, modelling & simulation, with the management of uncertainty and complexity being of particular interest, [170]. While analytics is a broad technical domain (see Table D.3 and Figure D.4 for context), areas of specific focus relevant to Alliance interests are new methods for intelligence analysis, media analysis, ISR sensors, signal processing, image analysis and weapon systems. Some of these methods explore foundational mathematical, computational, and physics-based approaches to improve the modelling and simulation of complex and complicated systems. In addition, improvements in computational capabilities and methods enable new practical applications in addressing the challenges of big data analytics [342]. Of particular interest is developing new statistical and analytical methods to assess data integrity [170], as well as advances in AI [343]. Other areas to note are [170]:

  - **Big Graph and Sparse Data Analytics**: Improved computational architectures and algorithms are being developed to improve the efficiency of big graph analytics [344, 345, 346] and sparse data analytics (e.g. manipulation of sparse tensors [347]). These approaches promise to significantly increase human-limited capacity for fusion, assessment and sense-making of large data streams and quantities of information in real-time.

- **Computational Methods**: Advanced computational methods have significantly increased the effectiveness of *Data*. While this is an area of constant development, three aspects are worth noting:

  - **(Secure) Multi-Party Computation (MPC)**: MPC supports local evaluation of sensitive data without sharing such data [348, 349, 350, 351]. Furthermore, data cannot be leaked or intercepted by an adversary due to the encryption techniques used with MPC. Early MPC protocols were impractical as they came with significant computation and communication overhead. However, recent developments enable such capabilities, focusing on efficiency and practical applicability in operational deployments or environments with strict privacy requirements (e.g. medical care [352]) as well as leveraging quantum information processing protocols[353]. Activity in this area is also related to AI research in the local processing of information and broader developments in Edge Computing.
  - **Probabilistic Programming Languages (PPL)**: Probabilistic Programming Languages generalise programming languages by "two added constructs: (1) the ability to draw values at random from distributions, and (2) the ability to condition values of variables in a program via observations." [354]. Increased computational resources have enabled improvements in PPL but are still limited by computational effectiveness and ease of development. They are, however, applicable to a wide variety of analytic and modelling problems [354, 355, 356].
  - **Quantum Computing**: Quantum computing is the only approach currently being explored that promises exponential improvements in computing performance [357] Quantum-optimised algorithms (e.g. Short's algorithm, quantum annealing, etc.) and specialised computing languages are undergoing rapid development [358, 359, 360].
  - **Computing**: While quantum computing receives most of the attention in this area, there are other trends to note. First, various computing paradigms are being explored, such as edge [361], fog [362], transparent [363], mobile and dispersed computing [119]. In addition, advances in semiconductor performance and architectures continue to lead to substantial (although not revolutionary) improvements in computing power, including that available within mobile devices. Finally, supercomputer development is an important research area, given the limited number of problems for which quantum computers are suited. As noted earlier, competition in this space is heated. While the US has recently announced the fast supercomputer in the world, the PRC is generally accepted as having the largest number and potentially fastest supercomputers available [364].

- **Modelling and Simulation**: M&S is a well-developed tool for predictive analytics. Emergent developments are ongoing, especially around the use of agent-based (e.g. [365]) and data-driven models [366, 367] where empirical models of real, complex processes and phenomena use libraries of data modelling primitives and human-model interfaces. Such systems are built for non-expert users and support the discovery and augmentation of datasets with limited or no human-in-the-loop. Research efforts include new computational primitives, increased use of AI and novel architectural/algorithmic approaches to enable fast and accurate simulations for practically intractable problems using electronic computers [153]. Improvements are also being developed in modelling physical phenomena to support scientific exploration. The DARPA lead Automating Scientific Knowledge Extraction and Modeling (ASKEM) is such a program [368].

Research in applied mathematics underlies the development of such analytical methods. The need for continued development of new applied mathematics is an underappreciated aspect of civil society [341, 369] and military operations [370]. These developments will be critical to our ability to deal with *Data* challenges. UNESCO notes the *vital role of mathematicians in tackling contemporary challenges ... [and] there may not be enough mathematicians to solve the complex challenges we face.*" [371, 372].

Novel Applications and Decision Making

Data does not exist in a vacuum and needs to be exploited to become actionable information and ultimately support decision-making. Application developments over the next years will focus on three core aspects: *group decision-making*; *improved interfaces and visualisation*; and the *application of data analytics* to enhance comprehension, data fusion, control, discovery, design and M&S. In particular, the increased use of digital twins (e.g. a virtual digital simulacrum of a natural system) supports the prediction of future failures or performance improvements through AI, analytics or M&S methods. The use of digital twins is expected to expand dramatically as AI/ML and advances in predictive analytics help extend its application beyond its industrial roots [373, 374, 375, 376].

Good advice is built upon good data and appropriate algorithms. Unfortunately, both are remarkably fragile, and research focuses on ensuring algorithmic fairness, understanding data, intelligibility, embedded logic, and protecting data integrity. The need for new and innovative developments in this area must be balanced with the increase in data and an ever-greater reliance on analytics and AI/ML to make sense of the data. While it is difficult to predict the exact nature of such advances, the pressure for better and fast analytical methods based on new and evolving mathematics and programming paradigms will grow with the increase in available data.

The following areas are of particular interest in terms of development over the next 20 years.

- **Group Decision Making**: Small group decision methods are a well-explored area of research. However, the increased effectiveness of social networking and media has opened up exploiting large-scale group decision-making. These approaches provide an alternate means of using the *"wisdom of the crowd"* to address complex and complicated societal problems [130]. This is part of a trend toward growing trend towards automated decision-making [377]. If anything, the digital response to COVID-19 has accelerated this trend. The conduct of the D3TX virtual exercise [33] and the S&T state-rate-impact survey conducted within the STO for this report (Appendix K) are simple examples of the power of such an approach. This development is closely tied to the opposite problem of wide-scale dissemination of disinformation and the development of empowered niche sub-groups actively working at cross-purposes. Both areas are under active research [378, 379, 380, 381] and are expected to increase in importance over the next decade.

- **Interfaces and Visualisation**: Collecting, curating and analysing information serves little purpose if this information is not used. Visualisation of *Data* lays the foundation for innovative ideas, dissemination and extraction of meaning or patterns within the data [382, 383, 384]. R&D continues developing advanced human-computer interaction, enabling interaction via natural language, gestures, facial expressions, visual and other modalities in context. Computational systems must be provided with contextual knowledge (physics, social, situational, etc.) to support rapid and appropriate analysis communication tailored for decision-making. Novel visualisation approaches, immersive realities, AI-enabled communication, neural interfaces, etc., are key technologies enabling seamless and tailored interaction [170].

- **C4ISR**: *Data* underpins decision-making and the development of unique and actionable insights from a defence and security perspective. As part of a broader C4ISR system-of-systems, NATO forces seek to *"out-think"* or *"get inside the OODA loop"* of an adversary. This advantage is a time-honoured objective of military and political leaders. A sample of highly relevant research in this area may be found in [153, 385, 386, 387]. Specific sub-areas of interest are:

  - **Data Fusion**: Fusing data from various sources with different spatial, domain and temporal characteristics is demanding. Once again, we expect to see AI and advanced analytics play a significant role in helping address these challenges. Some examples are:
    - All-Source Targeting
    - Employing Cross-Domain Kill-Webs
    - Exploiting Modular Multi-Sensor Fusion
    - Multi-Source Multi-Format Information Fusion
    - Multi-Domain Analytics
  - **Comprehension**: Understanding the presented information and potentially predicting future behaviour is essential for data management and battle networks. This relies heavily on developments in AI, M&S and Analytics. Areas of significant current and upcoming R&D are:
    - Anticipating Operational and Strategic Surprise
    - Causation in Complex Operational Environments
    - Health Analytics Using Smartphones
    - M&S of Social Media
    - M&S of Social Systems
    - Modelling Adversarial Activity
    - Semantics Forensics
    - Spatial, Temporal and Orientation in Complex Environments
    - Supporting Deterrence
    - Understanding Complex Hybrid Systems
  - **C2**: With new geopolitical developments, the example of the war in Ukraine, and the recognised need for multi-domain and multi-dimensional operations [388], decision-making and C2 are again rising to the fore as NATO seeks a C2 / Decision making asymmetry (e.g. faster, more accurate, more agile) [389, 390, 391]. More critically, we note [390]:

    > *"We've become focused on exquisite platform and system-of-systems designs for individual domain supremacy, but not on improving our command and control (C2) capability, ... we must eliminate the fixation on static plans, with their long decision timelines and approval processes and access to endless supplies. Dynamic operations must be the new normal, with the ability to operate when disrupted, distributed, and disaggregated when required."*

    Research, development and capability developments are expected on mechanisms to enhance information availability, collaboration and decentralisation of decision-making. AI, Space and RAS are expected to play a prominent role in developing such capabilities.

- **Digital Twins**: The push for increased digitisation of engineering and industrial processes provided the foundation for digital twins. Digital Twins Are a virtual digital simulacrum of a natural system, object or entity designed to cover the entire life cycle of the system being modelled. The term *digital twin* originated in 2002, but the first real-world application was by NASA in 2010 [392]. It

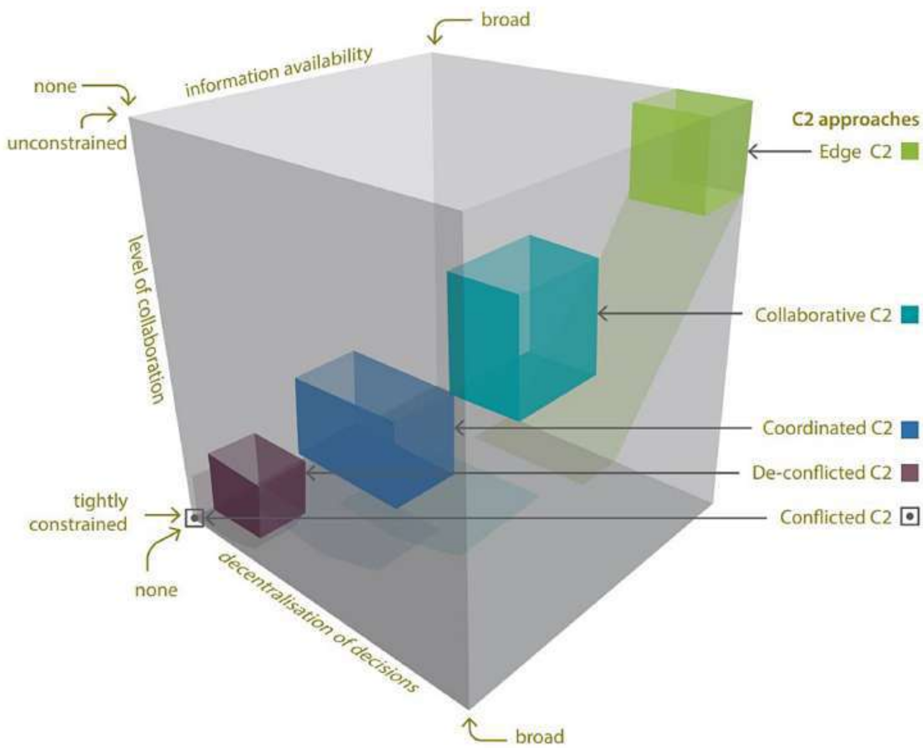


Figure D.5: *Six Types of C2, driven by physical, information and human requirements. [389]*

has since become widely used within the aerospace industry [393], but it is expanding into many fields, including the human domain.

The twin is typically updated with continuous feeds providing an accurate characterisation of the current system state. This characterisation supports the prediction of future failures or performance through AI, analytics, or M&S methods. Ultimately it supports the development of more agile and efficient processes [394, 400, 373, 374, 376, 401, 402, 403, 404, 395, 375, 396, 397, 398, 399]. The use of digital twins (highly detailed virtual models of a specific weapon system [375]) will become increasingly commonplace over the next ten years, relying on extensive embedded sensor networks, including those tied to the human and information aspects of such systems.

- **Social Media**: Changing from the physical to the human domain, the increased virtualisation of social and individual interactions have contributed dramatically to social and personal data availability. Much has been written about this virtualisation's positive and negative aspects and the development of *social media*. Its applications in defence and security include surveillance, sentiment analysis, knowledge and information sharing and low-cost video communication. Social media content grows ever-increasingly but struggles to deal with issues of veracity and value. This point, in particular, came to a head during the disinformation campaign during the COVID-19 crisis. DARPA [170], in particular, continues to explore the implications of social media in such areas as linguistic cues; patterns of information flow; topic trend analysis; narrative structure analysis; sentiment detection and opinion mining; meme-tracking across communities; graph analytics/probabilistic reasoning; pattern detection; cultural narratives; inducing identities; modelling emergent communities; trust analytics; network dynamics modelling; automated content generation; bots in social media; and, crowd-sourcing. As social media reaches more corners of society, it increasingly enables significant and subtle influences on the expression of collective political and social power. The technology has already demonstrated the potential to alter the nature of political and social discourse leading to new, rapid and decisive mobilisation of populations at the right place and the right time to achieve political and social objectives. Similarly, data collection in the social sphere allows an unprecedented understanding of human social behaviour and group dynamics. Continuing reliance on social media and its integration with increasingly sophisticated chatbots and virtual/augmented reality will be hallmarks of at least the next decade.

Distributed Ledger Technologies

Distributed ledger technologies, cyber-agents, improved visualisation, and predictive analytics support trusted information exchange and ultimately enhance human decision-making [405, 413, 414, 415, 416, 417, 418, 419, 420, 406, 407, 408, 409, 410, 411, 412]. It is seen as a critical enabler of the commercial web, ensuring the safety of business transactions. Distributed ledger technologies (DLT), blockchain among them (although the terms are often used interchangeably), employ peer-to-peer networks that allow members to maintain a copy of a shared ledger (an account of activities) while ensuring changes are recorded and protected. This lack of a middleman is compelling and increases transaction security if adequately encrypted. Distributed ledger technologies are an area of considerable commercial interest and continued research [421]. Their use in military operations is actively being explored [119], especially in the supply chain, personnel, C2, deployments, finance and asset management. As a mechanism for ensuring trust in digital transactions, it is expected that DLT will be even more widely deployed over the next decade.

Networks and Architectures

5G/6G

Research trends within advanced networks, including wireless technologies such as 5G/6G, generally focus on increased bandwidth, reliability, resilience, reduced latency, interconnectivity, reduced costs, and better overall performance. Critical networking trends and research areas are the increased use of AI/ML, the development of 5G/6G technologies, the increased use of virtual and augmented reality, cloud computing, IoT, edge computing, and a renewed focus on data/network security.

The roll-out of 5G has already highlighted the limitations of such technologies. As such, research has already moved onto the challenges of B5G (Beyond 5G) and followed on 6G technologies. These 6G technologies will begin to be available by 2030 and continue to be refined and developed over the decade. Such technologies are expected to support high-fidelity holograms, multistory (including haptic) interaction, XR, telepresence, real-time remote surgery, edge intelligence, smart cities, brain-computer interaction, ubiquitous autonomous systems (and swarms) etc. [422, 423, 424, 422]. However, to enable such technologies, with the necessary data rates, micro-second latency, ultra-high reliability and SWaP-C challenges, three critical developmental areas will need to be explored, as noted by [425, 426]:

1. Communication using Terahertz and optical frequencies for ultra-high-speed broadband access;
2. Cell-less architectures to enable ubiquitous 3D coverage; and
3. Intelligent networks to reduce costs and simplify the management of complex networks.

That said, it must be noted that 6G needs to be more well-defined. The increased need for faster, denser, and more reliable networks highlighted by 5G defines 6G for now (see Table D.4). 5 key technological changes that define 6G are bandwidth, time, security, AI, and ManyNet (seamless interconnection between diverse networks). AI is a particularly critical component, enabling optimisation and management of the network [425, 426] while simultaneously being one of the key drivers. By exploiting AI/ML, the network and smart devices will become cognisant and content-aware, facilitating autonomous decision-making and seamless adaptation to local conditions and agent requirements [425, 426]. With such an integration, the need for XAI (eXplainable AI) becomes even more acute.

Table D.4: *5G versus 6G*

Performance Measures	5G	6G
Peak Data Rate	10-20 Gps	1 $Tbps$
Per-User Data Rate	1 $Gbps$	>10 $Gbps$
Traffic Density	10 $Tbp/s/km^2$	>100 $Tbp/s/km^2$
Connection Density	$10^6 km^2$	$10^7 km^2$
Latency	50 ms level	<1ms
Mobility	350 km/h	>1000 km/h
Spectrum Efficiency	3-5x relative to 4g	>3x relative to 5G
Energy Efficiency	1000x relative to 4G	>10x relative to 5G
Coverge Percentage	70%	>90%
Reliabilty	99.90%	>99.999%
Frequency	$2 - 8GHz$	$95GHz - 3THz$
Multiplexing	CDMA (Code Division Multiple Access)	OFDMA (Orthogonal Frequency-Division Multiple Access)
Service	WWW, IoT, Wearables, Smart Manufacturing, Edge Computing, AI, Smart Farming	Assistive Technology, Edge Computing, Immersive AR/VR/XR Advanced AI, Autonomous Vehicles, Decentralized Business, Real Time 4D maps, Real-time biometric data, Holograms, Charge over network

Trust is another area of research for 6G technologies; in this context, quantum (communication) technologies may have an important part to play. Similarly, developments in distributed ledger technologies and post-quantum encryption are critical if 6G remains a secure protocol for communicating business, industrial and military information. As noted by [425, 426], 6G is a paradigm shift which includes Terahertz Communication (THz), Super Massive Multi-Input Multi-Output (SMMIOM), Large Intelligent Services (LIS), Holographic Beamforming (HBF), Orbital Angular Momentum Multiplexing (OAM), Laser Communication, Visible-Light Communication (VLC), blockchain-based spectrum sharing, and Quantum computing. Key technical advances will be necessary for cognitive spectrum sharing, photonics-based cognitive radio, innovative multi-dimensional architectural models, terahertz communications, holographic radio, novel antennas, and advanced modulation schemes. At the same time, 6G is conceived as covering all domains, including space and maritime (i.e. underwater), seamlessly linking these domains into an intelligent web.

Finally, S&T may be one of the major beneficiaries of 6G. Dense IoT agents, including sensors, will be enabled by 6G technology and simultaneously create massive volumes of data to be exploited. With the number of IoT devices already close to 10 billion, a socialised internet of things (SIoT) will support task decentralisation and dense inter-connectivity [427].

Significant technical challenges face a full roll-out of 5G technologies, predominately engineering. 6G technologies, building upon the promise of 5G, will require considerable scientific research if the challenges posed by 6G are to be met. Over 2020-2030, 5G technologies will dominate and spur innovation, while 2030-2040 will see incredible growth and development enabled by today's 6G research.

Architectures

Over the last ten years, an important evolution has been the development of new concepts for network and data architectures. A Data Architecture defines *"how data is managed–from collection through to* *transformation, distribution, and consumption."* [428]. New data architectures are key to blockchain, AI and the Internet of things (IoT) operationalisation. Notable concepts are data ponds, lakes, oceans, warehouses, lakehouses, hubs, mesh, and fabrics. As data complexity and volume growth, new approaches are expected to be developed.

Storage

An often underappreciated aspect of big data is the need for storage [429, 431, 432, 433, 434, 435, 436, 437, 438, 430], with the trade-off challenges of storage volume, physical size, read and write speeds and costs. While cloud storage is often seen as a solution for big data storage challenges, in the end, these rely on data servers with physical media. Current storage approaches are reaching the limits of associated physics, requiring more exotic approaches. Technologies such as helium drives, shingled magnetic recording (SMR), DNA storage, large memory serves NVRAM, Rack scale design, nitrogen-vacancy diamond storage, and 5D (quartz) glass optical storage [439, 440, 438, 436] hold promise but the energy and access speed challenges are not insignificant. DNA storage seems to be the most promising for large-scale information storage [441], and developments in biotechnologies will enable developments in this area. As critical as technologies are, developing new data architectures will also improve the management and storage of immense volumes of data. Improvements to data warehousing, lakes and fabrics will be required over the next five to 10 years, as well as data architectures that implement (biomimetic) *forgetting* strategies [442, 443] to reduce data storage and access issues.

Sensors

Sensors collect *Data*. Sensors provide the data in the physical domain and increasingly in the human domain. *Ubiquitous sensing* or *sensors everywhere* will significantly enable the growth of 5G communication and IoT. The concept of *sensors everywhere* refers to detecting and tracking any object or phenomenon from a distance by processing data acquired from high-tech, low-tech, active and passive sensors. Effectively everything will be a sensor, and every sensor will be networked. Military applications will be wide-ranging, including developing a multi-domain common operating picture, large-scale underwater sensor mesh networks, exploitation and weaponising of social media, automated logistics planning, autonomous systems, and integrated soldier systems. While sensor technologies are expected to evolve to support greater precision and accuracy, the most disruptive development will be the combination of further miniaturisation, reduced costs, novel (3D/4D) manufacturing and the sheer volume and wide distribution of sensors in the military sphere (e.g. SWaP-C). Advances in Materials technology also promise future sensors at the molecular, nano or quantum scale.

Advanced sensor technologies are driven by developments in other EDT areas, particularly Materials, Quantum, Biotechnologies, and AI/ML. Nevertheless, applying these technologies is critical for increasing surveillance timeliness, improving situational awareness, enhancing targeting effectiveness and effects assessment. Moreover, given that these capabilities underlie any successful military operation, it is also vital to design sensors capable of operating in a denied or deceptive operational environment and, in some cases, of doing so clandestinely [153].

Integration and weaving of sensors into ISR (Intelligence, Surveillance and Reconnaissance) systems present their challenges, especially in multi-domain operations (MDO). However, new sensor modalities, AI, Big Data, and Advanced Analytics have contributed to an exponential explosion of data and provide potential solutions across the operational domains. As a result, technological development of new sensor technologies or novel applications will be rapid over the next 20 years. Such developments include:

- **Smart Textiles**: Textiles imbued with molecular/nanoscale sensors providing real-time health and environment monitoring (e.g. CBRN) [444, 445, 446, 447, 448, 449] are expected to be widely available by 2030. These will complement existing biometric devices (e.g. smartwatches) [450].
- **Next-generation skywave Over-the-horizon (OTH)**: OTH (Figure D.6) and passive radar systems will provide wide-area air space surveillance, employing sophisticated data processing and multiple-input multiple-output (MIMO) technologies [451, 452, 453, 454, 455, 456, 457]. Passive OTH

radar will likely be in a mature prototype state within 5-10 years, with fully fielded systems in place in the 10-15 years. Air target detection ranges could increase from 350km to 1500km. Building on decades of experience (Australia and the US in particular), R&D on next-generation high frequency (HF) OTH radars continues, as they are useful for persistent long-range air space, counter-cruise missiles and counter-stealth surveillance [210, 458, 459, 460, 461]. These developments are driven by advances in new electronics, AI/ML and an improved understanding of atmospheric physics.

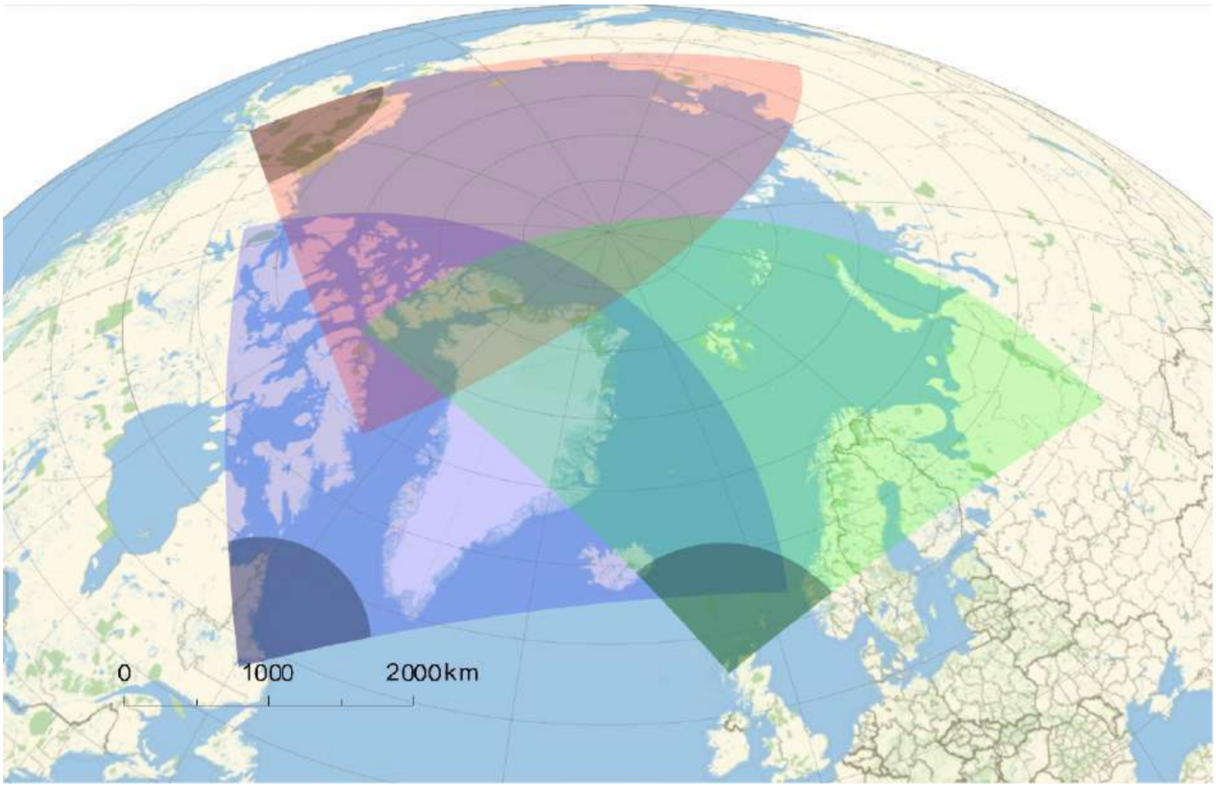


Figure D.6: *Hypothetical OTH Northern Radar Coverage.*

- **Computational imaging (CI)**: CI [462, 463, 464] holds great promise to revolutionise EO/IR sensors and provides significantly increased sensitivity. CI refers to image formation techniques that use digital computation to recover an image of the scene. Compressive sensing (CS), a CI subset, involves capturing a smaller number of specially designed measurements from the scene to recover the image or task-specific scene information computationally. CS has the potential to acquire an image with similar information content to a large format array while using smaller, cheaper, and lower bandwidth components. More significantly, data acquisition can be designed to capture task-specific and mission-relevant information guided by the scene content more flexibly. CI can potentially address SWaP-C concerns while enabling simultaneous target acquisition and situational awareness (multiplexed imager), perception range extension (Non-Line-of-Sight Imager, multispectral imaging), and multipurpose imagers. By some measures, CI is in the process of killing off digital cameras, similar to how digital photography ultimately made film obsolete [465].

- **Microwave photonics**: Microwave photonics is on the verge of delivering higher performance, lower power, more robust sensing, and wireless communication on the battlefield [466, 467]. Microwave photonic radars have been recently proposed given *"the advantages of generating and processing wide bandwidth microwave signals, reconfigurability, high immunity to electromagnetic interference compared to microwave electronic radar"* [468, 469].

- **Quantum sensing**: Quantum sensing, which, in the long term, will generate a revolution in sensing technology, enables very high-sensitivity sensors. These, in turn, could potentially be capable of long-range detection of aircraft, submarines or subterranean activities. In addition, this capability allows the development of smaller higher, performance sensors to monitor weapon system health and performance. Appendix I presents a more thorough discussion.

- **Maritime**: Researchers seek to improve persistent oceanographic sensing and maritime situational awareness [153] through networks of low-power microelectronics and advanced analytics.

  Considered a vital part of the Mosaic warfare program of DARPA, the OoT *"seeks to enable persistent maritime situational awareness over large ocean areas by deploying thousands of small, low-cost floats that form a distributed sensor network"* [470]. Such OoT technologies will provide significant surface and subsurface detection capabilities [471, 472]. Over the next decades, this IoT approach is expected to be expanded and extended to other domains (space, air, land). In addition, synthetic biology may play a role here as genetically engineered biosensing platforms may augment more traditional sensors [473].

Figure D.7: *Ocean of Things - CREDIT: DARPA [470].*

  Large numbers of heterogeneous, environmentally friendly and networked satellite buoys are being used to collect enormous quantities of data organised in data lakes. Big data and advanced analytics explore, assess, and discover new oceanographic processes and human activity. This will support the development of methods for fusing diverse spatial-temporal data and leveraging IoT technologies.

- **Air**: Extending air situational awareness into complex and urban terrain is a growing challenge, driven in no small measure by the increased use of commercial and military UAVs. However, experience in Ukraine has highlighted just how useful such capabilities can be. Therefore, R&D is being undertaken to create an IoT architecture of widely distributed (city-scale) and increasingly autonomous air platforms [42, 474, 475]. Such an *"Aerial Dragnet"* will allow rapid UAV platform detection, tracking, classification and engagement. In addition, SWaP-C challenges are being addressed to enable the integration of signal processing, sensors etc., in supporting autonomous systems.

- **Low Power Sensors Networks**: Event-triggered, very low power untethered and unattended sensors [170, 476, 477] create an opportunity to develop persistent ISR networks capable of covert operation for extended periods measured in weeks to years. This research seeks to avoid IoT sensors' power and endurance limitations (light, heat, sound, etc.) by creating event-triggered *"near-zero power"* sensors. Creating a digital backbone for these networks requires R&D on low-power, long-range and low-cost communications, so-called low-power wide-area networks (LPWAN) [119, 478, 479].

- **RF (Radio Frequencies)**: Research and experimentation with novel RF sensors span various topics and applications.

- **Thermal**: Research in Hypersonics and Propulsion requires precise high operating temperatures. Developments in enabling and electronics significantly improve high-temperature sensing systems [210], allowing more precise modelling and improved design performance. At the opposite extreme, ratiometric nano-thermometers [119] enable precise non-invasive nanoscale measurements, including at the individual cell level.

- **Strain**: Developments are being made in embedded strain measurements. This research seeks highly flexible and stretchable sensors in soft robotics, artificial skin, and biometric monitoring [119, 449, 480].

- **Radiation**: New ultra-fast radiation detectors allow for rapid special-temporal measurements of charged particles. These detectors are used in many high-tech products, including cell phones [119].

- **LiDAR**: Great strides have been made in SWAP-C issues associated with LiDAR. This has led to increased innovative use of 3D LiDAR technologies [33, 481, 482, 483, 484], in particular their use on UAVs for rapid 3D terrain mapping.

- **Optical**: Software-defined cameras are being developed to create software-defined optical sensors that can be tailored to provide more actionable information across multiple spectral bands, increased resolution, frame rate, or depth information [210]. Work on SWaP-C issues has achieved remarkable success, with high-resolution cameras the size of a grain of salt [485].

- **Smartphones**: Modern cell phones collect vast amounts of data; research in the public and military spheres is ongoing on new analytic techniques to leverage this data. This biometric information may provide remote, continuously recorded, real-time health, physiological and behavioural assessments [210].

- **Diagnostics**: New sensor technologies are improving medical diagnostics. These new technologies include [119] photoelectrochemical aptasensors [486], photochemical immunosensors [487], photoinduced force microscopy [488] and remote photoplethysmography [489]. These technologies have applicability to CBRN defence and countermeasures, as well as health monitoring.

Cyber & Resilience

Dealing with data integrity and trusted algorithms is a growing concern, as is the robustness of *Data* methods. This matter includes tools for identifying and attributing malicious social or cyber actors and developing RED-team cyber agents to assist cybersecurity operators in determining cyber-physical-human vulnerabilities. Cyber is a broad area [490, 498, 499, 500, 501, 502, 503, 504, 505, 491, 492, 493, 494, 495, 496, 497] but the following areas of to be noted in the context of embryonic S&T:

- **Algorithmic Fairness**: Given the increased reliance on *Data*, fairness, bias, accountability, and transparency in data and algorithmic approaches are becoming a societal issue. Biased data (sex, race, gender, social status, religion etc.) may unconsciously prejudice results. Algorithms (primarily coded into a decision system) may unintentionally embed technological, cultural, doctrinal, policy, and ethical preferences [119]. In the case of AI systems, this is connected to research in Explainable AI.

- **Safe Textual Data**: Text is data, and that data's quality drives the analysis's quality. It is imperative to develop automated technologies that will ensure the veracity of documents or streaming data. In addition, such systems will need to reject inaccurate or malevolent data [153].

- **Tamper-Proof and Resilient Systems**: Ensuring a secure information processing chain against information manipulation that might occur at any level. This includes ensuring the safety of the programming, algorithmic and computational sub-systems [33].

Military Implications

BLUE

There are many potential defence applications of these scientific and technological developments. In particular, *Data* will impact operational and enterprise capabilities.

Excelling at *Data* has the potential to create a NATO decision and knowledge advantage grounded in the innovative collection, processing, exploitation, dissemination and fusion of immense and wide-ranging data sources and information products. Success in this area would support a more refined and comprehensive understanding of tactical, operational and strategic environments and courses of action. Areas most likely to be affected include:

Enable

NATO's basic business processes, policy development and strategic planning will benefit from an increasingly sophisticated and evidence-based approach, including real-time monitoring of the impact of decisions and predictive assessments of options through advanced M&S.

Prepare

Virtual environments and bioinformatics will support improved training for operations. Physiological and psychological state monitoring will maximise overall human performance and readiness through increased health and safety monitoring and injury protection. Algorithmic optimisation of individual and team performance & readiness will also be possible.

Project

Counter-social-engineered and cyber agents (e.g. bots) to auto-identify, disrupt and investigate bot-mediate social and cyberattacks [170].

Sustain

The increased integration of weapon system health monitoring sensors, real-time inventory monitoring and the use of *digital twins* will significantly increase the efficiency and effectiveness of the logistic system while reducing life-cycle costs. In addition, a greater understanding of the current status of munitions and their ability to achieve mission objectives will also be possible through *Integrated Munition Health Management* models enhancing relative safety, reliability and performance risks.

Inform

The proliferation of advanced sensors and the increased use of autonomous systems will dramatically increase NATO's ability to detect, classify, recognise, identify and engage threats across physical and virtual operational environments. Adaptive solid-state power amplifiers and optimised waveforms will support simultaneous search and track capability for the interdiction of airborne targets, resulting in faster and more accurate ISR and multiple intelligence source analysis exploitation. Passive radar reduces the vulnerability of systems to electronic countermeasures and increases the detection capabilities of stealth targets. Advanced processing at the sensor itself will result in lower bandwidth requirements, faster sensor-to-shooter times and more reliable data transfer. Capabilities inherent in devices that enable social media, such as video, audio, text, GPS, proximity detection, and others, will transform traditional ISR capabilities. Fusing social network sensing with conventional sensor data fusion will enable: multimodal content filtering and summarisation; data fusion for event detection; event tracking; analysis of social dynamics; and anomaly detection.

Improved mapping of mission areas for planning & preparation, and rehearsal environments will support operational planning and increased situational awareness (SA). This increased SA includes improved patterns of life, human terrain and anomaly detection. This awareness will be further enabled by enhanced low-power display capabilities for soldier systems, embedded analytics (e.g. AI) and increased information flow between the tactical and command levels. Geo-tagged soldier systems and social media data will also be used to generate increasingly accurate environmental information. Deep learning used in the deciphering of internet content has the potential to identify security-relevant information through social behaviour on the Internet merged with content extraction from multiple text documents (even if specific intent is not explicitly referenced). Fusing social media data with traditional sensor data provides a more dynamic and accurate human-terrain mapping, and common operational picture [506, 507].

Contextual programming will enable search engines to move beyond simple keyword searches by discerning the intent behind the search and offering more behaviour and location information.

C3

Data is enabled in no small measure by *ubiquitous computing*, that is, computing anywhere, anytime and on any device. Ubiquitous computing has the potential to provide real-time decision support to the individual soldier at all times and in all places, especially when integrated with military mobile networks and mission cloud computing. Such mesh networks of connected devices will allow BLUE forces to leverage and exploit distributed data structures and cloud computing services. It also encompasses software-driven functionality, which can process incoming data at the sensor before transmission. It exploits advances in encryption that will enable assured information transfer across a network.

Vast quantities of sensor-targeted information. This approach may predict security risks from a deep analysis of personal contacts. Social network data (ISR, logistics, bioinformatics, human terrain, etc.) will support a more comprehensive understanding and approach to the operational environment. Combined with AI, this will enable a more holistic approach to operational planning, courses of action analysis and (kinetic and non-kinetic) targeting. Improved understanding and modelling of adversarial group behaviours will help enable the ability to generate courses of action that are disruptive to their goals and activities.

Exploiting C3 Warfare and the associated Battle Network tactical, operational or strategic purposes is also an area of considerable R&D. Much of this work involves understanding how to link new sensors and capabilities into a seamless and compelling whole. Equally, this work leads to understanding how to defend from and exploit a weakness in opposing networks. Cyber research is a critical element, both defensive and offensive.

Secure communication and data storage is essential in military operations. Databases are the traditional means to store and maintain structured and related data. More recently, distributed ledger technologies (e.g. blockchain) have emerged and been used as the distributed, transparent, and permanent data management technology underlying the Bitcoin cryptocurrency. The increased use of blockchain technologies (along with AI-enabled defensive cyber-bots/agents, quantum key distribution (QKD) and post-quantum encryption) will significantly increase the Alliance's ability to ensure trusted communications and data storage.

A continuing trend away from centralised-only data silos is also noted. Instead, smart devices will collaborate, while processing will increasingly be at the edge where the data was born and exists. Machine-learning algorithms can adjudicate *peer-to-peer* communications and decisions in real-time.

RED

RED *Data* is expected to develop along the lines outlined for BLUE. RED forces will seek to develop their decision advantage and get inside the NATO OODA (Observe-Orient-Decide-Act) loop. Further:

- *Data* will increase the effectiveness and expansion of RED operations into non-traditional domains, enabling sophisticated targeting of individuals and social groups via and across the instruments of national power (*DIME*: diplomatic, information, military and economic).

- Increased NATO use of *Data* will introduce vulnerabilities in command decision-making that sophisticated and non-sophisticated RED opponents may exploit. The focus of targeted cyber or information attacks will become more covert and explicitly designed to undermine BLUE decision-making and destroy trust. Over-reliance on *Data* in decision-making will increase the risk of damage from cyber/information attacks.

- Increased globalisation and commodification of information and sensors means that potential adversaries will have access to much of the same data, commercial tools and encryption methods as BLUE.

- Proliferation of access to mobile computing solutions by adversaries is to be expected as these will be increasingly commercial.
- Hybrid or memetic warfare employing social media deception, diplomatic *warfare* and influence operations undermine, delay or frustrate BLUE forces, nations and populations.
- The potential to locate camouflaged, stealthy, protected or submerged targets through the processing of large volumes of data from persistent active and passive sensors will have a significant tactical and operational impact on future Alliance operations. For example, the US nuclear triad could be highly destabilised [86].

Interoperability

Interoperability challenges are expected in the following areas:

- **Technical Obsolescence**: Rapid RED and BLUE *Data* technological evolution will require constant investment to maintain a technological edge and ensure operational resilience. This will challenge Alliance nations to keep a common technological and interoperable force, especially as the NATO enterprise and operational commanders rely on *Data*-engendered near-real-time feedback, increased situational awareness and improved operational effectiveness.
- **Network Allocation**: The EM Spectrum is becoming more commercial, congested, contested and competitive globally from the commercial use of advanced radio-frequency technology. Alliance agreement on spectrum allocation and conflict will need to be undertaken.
- **Data**: Distributed data and verification structures will need to be developed to allow nations to maintain ownership and control of data while sharing within a coalition. Big data raises concerns about security, privacy and governance that must be addressed at an Alliance level. Development of policies on data collection, retention, exchange, curation, classification, bandwidth, taxonomies and privacy will be necessary.
- **Unique Standards**: NATO operational and enterprise environments have unique characteristics not shared by commercial and civil environments, including reduced risk tolerance and policy constraints. Legal issues may also become a concern as commercial interests seek to protect underlying intellectual property (IP) (e.g. explainable AI), thereby limiting *explainability* of recommended courses of action or assessments.
- **Standards**: National adoption of critical *Data* technologies (e.g. 5G) may create a significant digital divide due to differing threat perceptions and adoption of underlying technologies. A lack of standards and the development of incompatible or *untrustworthy* systems may limit NATO's ability to share C4ISR and other sensitive data.

S&T Development

State of Development

Data will significantly impact (defence) S&T through meta-analyses of existing scientific and technical knowledge. This meta-analysis, in turn, will lead to the creation of novel materials, the development of new and better sensors, the discovery of new underlying science etc., which will directly impact the development of new NATO capabilities.

Data research is highly interdisciplinary, with strong commercial and open-source underpinnings. Key areas of research and development are identified below.

RAS

DATA R&D will enable new, distributed, low-power and sensitive autonomous sensors capable of large-scale mesh behaviour and self-organisation (ubiquitous sensing). This includes developments in analysis, fusion and assessment of signals from autonomous sensors and edge-computing.

Biotechnology
Developments in DATA will support new, distributed, low-power and sensitive sensors capable of large-scale mesh behaviour and self-organisation (ubiquitous sensing). This includes developments in analysis, fusion and assessment of signals from passive sources (e.g. bio-engineered), bio-social sensors, multi-sensor/multi-domain sources, and edge-computing.

Energy
DATA advances will support the development of novel technologies to optimise network resources, data through-put and (cognitive) spectrum management (including operations in a contested and congested environment with limited knowledge of other appliances, vehicles or sensors on the network) for distributed applications or sensing. The research will explore new communication modes (e.g. 5G), mesh networks, post-quantum encryption methods and the increased use of cognitive (AI) techniques.

STO Activities

Several STO Scientific and Technical Committees have produced significant research on *Data* technologies. Many panels have ongoing activities on several topics aligned with these technologies. The following is a sample of ongoing activities:

- AVT-368: Data Fusion and Assimilation for Scientific Sensing and Computing
- AVT-369: Digital Twin Technology Development and Application for Tri-Service Platforms and Systems
- AVT-373: Emerging Technologies for Proactive Corrosion Maintenance
- AVT-382: Dynamic Reconfigurable Mission Planning for Improved Readiness of Autonomous Military Vehicles
- AVT-ET-227: Climate Change: Mitigation and Impact on NATO Platforms
- AVT-ET-231: Criteria for Security Evaluation of Tamper Protection Technologies for Military Systems
- AVT-ET-233: Platform Implications for Hybrid Space Architectures for NATO Missions
- HFM-ET-205: Digital Mental Performance Training for Optimal Human Function
- HFM-SAS-357: Standards for Military Personnel Data and Analytics Exchanges
- IST-162: Cyber Monitoring and Detection Capability for Military Systems
- IST-174: Secure Underwater Communications for Heterogeneous Network-Enabled Operations
- IST-176: Federated Interoperability of Military C2 and IoT Systems
- IST-180: Network Management & Cyber Defense (NMCD) for Federated Mission Networking (FMN)
- IST-185: Communication Networks and Information Dissemination for the Tactical Edge
- IST-186: Blockchain Technology for Coalition Operations
- IST-187: 5G Technologies Application to NATO Operations
- IST-194: Adaptive Networks at the Tactical Edge
- IST-196: Cyber Security in Virtualized Networks
- IST-199: Free-Space Optical Communications
- IST-201: Federated Communication and Collaboration Services at the Tactical Edge
- IST-202: Federated Tactical Networking
- IST-203: Wireless Communication Standardization in NATO
- IST-ET-117: Data Hiding in Information Warfare Operations
- IST-ET-120: RF Finger Printing of Drones
- MSG-191: NATO Standards for Federated Simulation and Services for Integration, Verification and Certification
- MSG-195: Modelling and Simulation as a Service – Phase 3
- MSG-200: Modelling Cyber Domain Entities and Events Within Distributed Simulations
- MSG-205: Allied Interoperability and Standardization Initiatives for Digital Twins
- MSG-213: M&S in Support of Building Resilience and Refugee Flow Management
- MSG-214: M&S for Operational Mission Support
- MSG-ET-053: Allied Interoperability and Standardization Initiatives for Digital Twins
- SAS-153: Best Practices on Cost Analysis of Information and Communication Technology

- SAS-155: Developing a Standard Methodology for Assessing Multinational Interoperability
- SAS-157: Automation in the Intelligence Cycle
- SAS-158: Employing AI to Federate Sensors in Joint Settings
- SAS-177: Defending Democracy in the Information Environment – Foundations and Roles for Defence
- SAS-181: Exploiting Reinforcement Learning to Achieve Decision Advantage
- SAS-HFM-ET-FE: Early Warning System for Cognitive Warfare in Cyberspace
- SAS-IST-171: C2 Services in Multi-Domain Operations for Federated Mission Networking (FMN)
- SAS-IST-179: Semantic Representation to Enhance Exploitation of Military Lessons Learned
- SAS-MSG-180: Modelling & Simulation-Wargaming Integration for Intermediate Force Capabilities (IFC)
- SCI-349: Heterogeneous Data-Driven Space Domain Decision Intelligence
- SCI-IST-ET-060: Overview of Maritime Situational Awareness Activities Within STO, ACT, CMRE and the NATIONS.
- SCI-SET-353: C-UAS Mission-Level Modelling & Simulation
- SET-284: Enhanced Situation Awareness Using Active-Passive Radar Systems in Military Scenarios
- SET-286: Acoustic and Seismic Sensing of Threats in Urban Environments
- SET-290: AI for Military ISR Decision Makers
- SET-295: RF Sensing for Space Situational Awareness
- SET-310: Assessment of EO/IR Compressive Sensing and Computational Imaging Systems
- SET-312: Distributed Multispectral/Statics Sensing
- SET-313: Advanced Methods for Hyperspectral Data Exploitation
- SET-319: New Mathematical Frontiers for Multi-Dimensional Radar Systems
- SET-320: New Frontiers in Modern Passive Radar
- SET-ET-128: Open Data RFT/OT Initiative
- SET-ET-129: Algorithms as Observers: The Future of Imaging System Design, Modeling and Testing
- SET-HFM-314 Multi-Omic Data Science Research Workshop

Scientometric Analysis

The keywords associated with Data as derived from STEAM analysis are shown in Figure D.8.

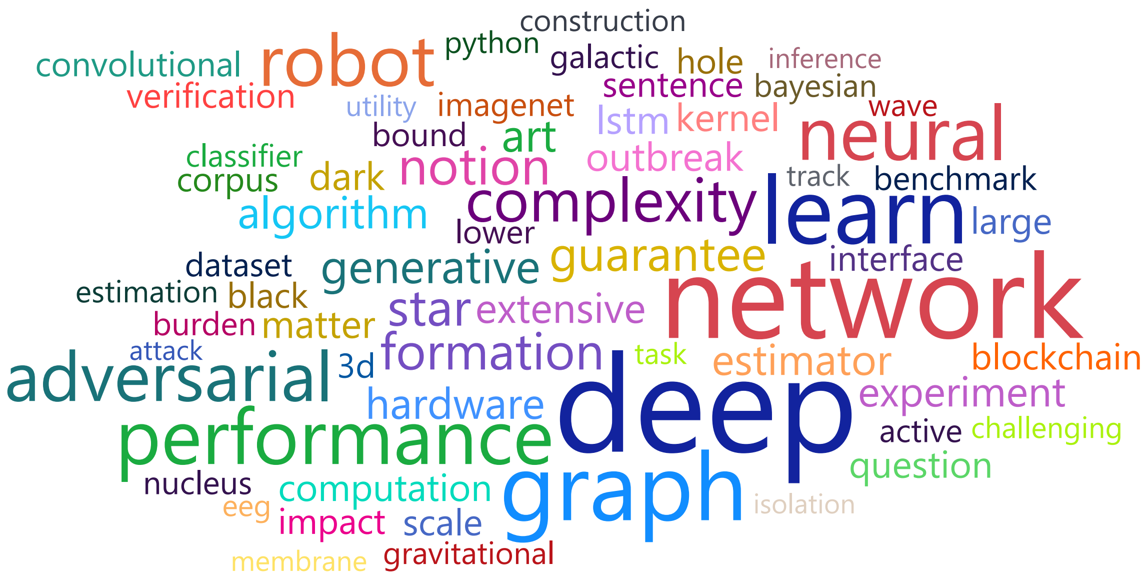


Figure D.8: STEAM - Big Data, Advanced Analytics and Information Communication Technologies (or Data) - Keywords

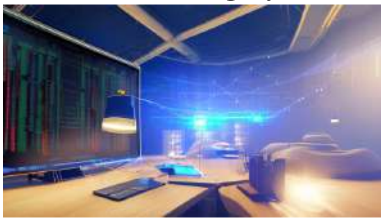
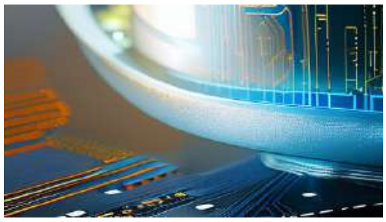
Survey Results

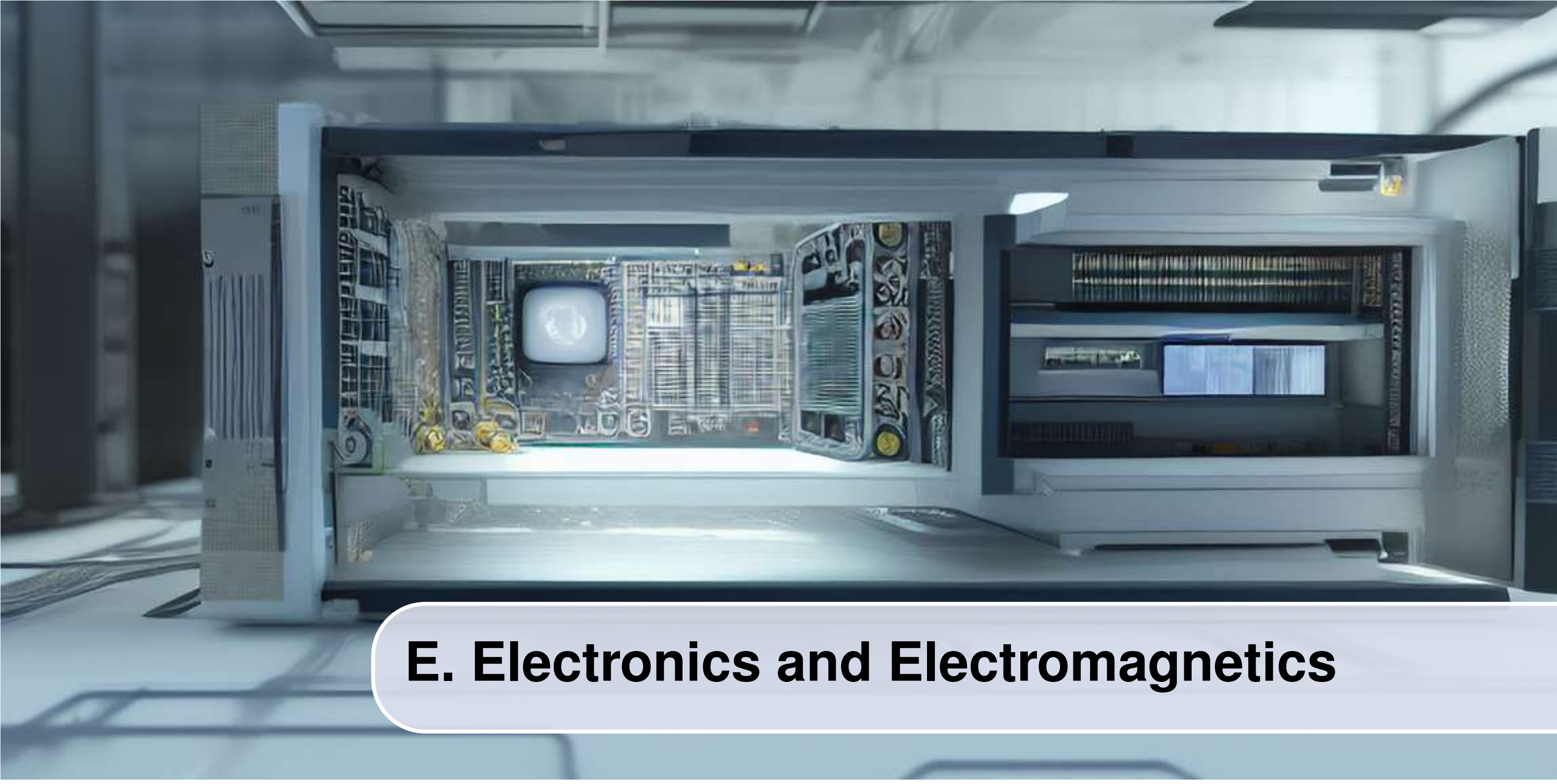
The following table presents the assessed potential impact, state and rate of development and identifies areas for focused research.

Table D.5: Big Data, Advanced Analytics, and Information Communication Technologies (Data) 2023 - 2043.

EDT	Technology Focus Areas	Impact	TRL	Horizon
Data	Advanced Computing & Software	High	7-8	2025-2030
	Novel Applications & Decision Making	High	5-6	2030-2035
	Distributed Ledger Technologies	High	5-6	2025-2030
	Innovative Networks	High	5-6	2030-2035
	Networked Sensors & Sensing	High	5-6	2025-2030
	Data Storage	High	7-8	2022-2025
	Cyber	High	5-6	2025-2030

Conjecture Card: Data and Information Communication Technologies

A. Real-Time Video Feeds  Access reliable real-time unhackable streaming video feeds from hand-held or head-mounted 6G low-observable wireless devices.	**B. Information Integrity**  Software agents assure the source and integrity of information, networks and data to prevent the insertion of distracting or false information by hackers or cyber agents.	**C. Commercial Networks**  Military use global, always-on commercial networks for unbreakable encrypted communication and data transfer.
D. Situational Awareness  Know the location and history of every individual or item in an organisation or operation using digital twins and the IoT.	**E. Trusted Systems**  Trusted information exchange in zero-trust environments, for example, to exchange money or control checkpoints.	**F. Assured Connectivity**  Store and retrieve strongly encrypted data/information across the network, so it is always accessible and recoverable.
G. Courses of Action  Simulate billions of potential courses of action in near real-time, and identify optimal solutions while adapting recommendations to real-time sensor information.	**H. Global Intelligence**  Conduct continuous global ISR and target acquisition in all operational domains while fusing data into a single coherent, rich intelligence system.	**I. Algorithmic Advantage**  Optimise enterprise functions and provide predictive assessments in-real time to support enterprise decision-making and capability development.
J. Collective Mind  6G technologies link groups of soldiers and autonomous systems into a more effective and cohesive unit.	**K. Novel 3D Printed Antennas**  Novel small antennas greatly expand the use of the EM spectrum for communication and sensing.	**L. Massive Data Transfers**  IoT and cloud computing create massive data lakes and require data transfer rates of staggering size (Zettabytes/sec).



E. Electronics and Electromagnetics

Electronics
"Moore's Law - The number of transistors and resistors on a chip doubles every 24 months" - *G. Moore*

Definition

Electronics & Electromagnetics (E&EM)
Electronics refers to the branch of technology concerned with the design, fabrication, and operation of electronic devices and systems. These devices and systems include transistors, diodes, integrated circuits, lasers, optical fibres, and other components that use the flow of electrons to perform a wide range of tasks, such as computation, communication, and control [508].

Electromagnetics, on the other hand, is the branch of physics that deals with the study of electric and magnetic fields (EMF) and their interactions with charged particles. Electromagnetics is important in many areas of electronics, including the design and operation of antennas, radiation and transmission lines, microwaves, infrared X and gamma rays, and electromagnetic compatibility [509].

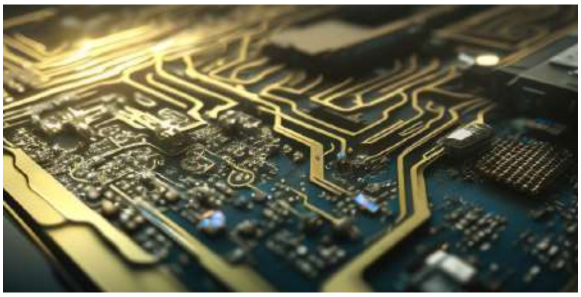
Keywords

Electromagnetic spectrum · Electromagnetic dominance · Electronic reconnaissance · Transistors · Diodes · Integrated circuits · Lasers · Optical fibres · Magnetic fields · 4D antennas · Microwaves · Infrared rays · X-rays · Gamma-rays · Silicon-based electronics · Photonic quantum circuits · Cognitive radio · Radio Frequency · Advanced electronics · Directed Energy Weapons · 2D materials · Neuromorphic chips · Biomimetic chips · Hyperdimensional computing · Neural circuits · Democratised chip design · 3D/2.5D chips · Ultra-low frequency · Very low frequency · Wideband · 4D arrays · Photonics · Signal processing · Spectroscopic sensing · Silicon photonics · Silicon chips · Optomagnotics · Improved optical signalling · Neuromorphic photonics · Topological photonics · Compact radiating photonics · Nanolasers · Free-space optical rays · Light detection and ranging (LiDAR) · Modular Optical Aperture Building Blocks (MOABB) · Cognitive sensors and radars · Spoofing · Adaptive camouflage · High-frequency high-power overmatch · Adaptive spectrum management · Directed energy weapons (DEW) · Electronic Warfare (EW) · Electromagnetic metasurfaces ·

Developments

Overview

Technological progress is contingent upon developing new electronics and controlling the electromagnetic (EM) spectrum. The famous Moore's law encapsulates our ability to scale first-generation silicon-based electronics at a rate that doubles transistor counts roughly every two years. However, this scaling will encounter hard physical limits within the next ten years, necessitating new approaches to electronic systems [510] that exploit novel concepts, tools, materials, and designs. Therefore while continued refinement and optimisation of silicon-based electronics will be the preoccupation of industry over the next ten years, new developments exploiting novel materials, designs, architectures (combining memory and computation), physics (magnetic states, electron spin properties, topological insulators, phase-change materials, trapped-ion & photonic quantum circuits), photonics, AI-enabled design tools and neuromorphic chip designs are being explored to continue to scale computation beyond the limits of silicon [153]. At the same time, *"designed in"* electronics security must be undertaken to ensure a cyber-safe processing and computation environment.



The EM is becoming an increased area of competition and congestion. Therefore, developments are needed to maximise and optimise (e.g. cognitive radios and frequency management) the use of limited EM spectrum while simultaneously considering the challenges of electronic warfare. Furthermore, technological progress in many emerging and disruptive technologies (EDTs) is contingent upon developing new electronics and controlling the EM spectrum. Among these technical challenges is moving beyond first-generation materials (e.g. silicon).

Novel research in Electronics and Electromagnetics (E&EM) continues briskly. Over the next 20 years, five main areas of R&D activity in this field are seen to be disruptive: **(1)** Advanced Electronics; **(2)** Antennas; **(3)** Photonics and Lasers; **(4)** Spectrum; and, **(5)** Directed Energy Weapons.

Advanced Electronics

The ability to develop new electronics is reaching the fundamental limits of silicon-based physics, which will impose hard limits on Moore's law. Nevertheless, it is also true that promising research is ongoing, looking at various means of moving beyond silicon [511]. Much of this research is clustered into three broad categories [153]: Materials, Architectures and Design.

- **Materials:** Research will develop new non-silicon-based materials supporting following generation logic and memory. Novel methods of computing are being explored based on non-traditional intrinsic material properties, mixed materials (compound semiconductors) and cryogenic computing (leading to a potential order of magnitude improvement in electrical usage or performance) [153]. In particular, graphene and other 2D materials are promising developments in creating new chip (photonic and 3D designs) technologies [512, 511]. Second-generation materials [513, 444], such as GaA (gallium arsenide) and third-generation materials, such as SiC (silicon carbide) and GaN (gallium nitride), hold out the promise of reduced power, noise, heat and size. Many countries, including China, are investing in these technologies to embrace a potential technological leap-ahead opportunity [514, 515] unencumbered by current economic and technological restrictions.

- **Architectures:** Rethinking circuit architectures at chip and board levels offers improved performance and cost reduction using silicon-based transistors [153]. Specialised circuits and AI/ML to assist and automate designs provides further opportunities to improve performance and reduce heat or energy usage. Other promising areas are biomimetic chips such as **neuromorphic** [516] and **hyperdimensional computing** [517, 518], and exploiting specialised properties of neural circuits, including in-memory computation. Such chip design approaches are especially valuable for AI/ML. 3D integration of chips provides an additional means of increasing computing performance but presents extra heat, energy and noise challenges [519].

- **Design:** Improving chip design is another means of improving chip performance. Much of this area's work exploits AI/ML to improve the design and optimisation of chip layout [511, 520, 521]. While this dramatically opens up new architectural options and improves chip efficiency, it also has the potential to "democratise" chip design, making sophisticated chips more widely available and potentially open-source [522]. However, designing 3D and 2.5D chips [523] will also present severe challenges to concepts and understanding of the physics involved [524].

Antennas

As military and commercial communication or sensor systems are miniaturised, size, weight, power and cost (SWaP-C) considerations become more critical. However, reconsidering the design of such systems often comes up against the physical limits and vulnerabilities of the antenna. As a result, research into new antenna designs is of interest for defence applications. While developments in this area are extensive, less-known examples of research of potential interest are:

- **ULF/VLF transmitters:** Ultra Low Frequency (ULF, 0.3 kHz to 3 kHz) and Very Low Frequency (VLF, 3 kHz to 30 kHz) are beneficial frequencies for underground and underwater communications [511]. Given the large wavelengths, classical antennas are often a kilometre or more in length [153]. A new approach to mechanically manipulated magnetic/electrical fields can substantially reduce antenna size (to around Ĩm). This expands the use of long-range wireless comms, including underground and underwater.

- **Wideband:** The development of antennas for ultra-broadband emitters and receivers can provide a resilient and secured communication channel for military operations [525], with enhanced abilities to circumvent current electronic warfare jamming capabilities [153].

- **4D arrays:** Manipulation of antenna arrays whereby individual elements are selectively turned off and on, creating unique and useful sidebands. These sidebands are suitable for multi-channel transmission, and smart beamforming [526, 527].

- **Fully digital RF structures (FDRFS)** [528] range widely across the spectrum from defence radar antennas, emergency guidance and coordination systems, navigation satellites, communications, aircraft survivability systems. Modern wireless RF systems are advancing via digital technologies to improve their capabilities when operating in severe EM environments. Comprehensively digital RF systems are critical for mission success reliant on communications, information and data on land, at sea or in space, allowing for innovative and unique new operational capabilities. Originally, wireless devices for radar, communications, navigation, and other RF systems relied purely on analogue components and techniques (transmitter, receiver, and signal processing), with the information passed from one module to another in the form of analogue input and output signals. However, due to the increasing miniaturisation and integration of digital parts and the sustained increase in processing power, digital signal processing has ensured consistent overall system performance. Radio-frequency signal processing, known as SPAR, is also an area of research with functional and implementable innovations within 5 to 10 years.

Photonics and Lasers

Photonics, or the study of manipulating light in a medium for transmitting information, is a well-established science. Nevertheless, it is a field that yields new and exciting applications, including breath-taking options for quantum computing [529]. Applied physics research is still being conducted to understand the basic photonic science, the interactions with integrated circuits, and their application in communications, signal processing, spectroscopic sensing, and imaging [153].

The growing area of silicon photonics is noted [529, 530, 531, 532, 533], which uses silicon chips to manipulate light rather than electrons as in conventional electronics. As a result, power consumption, costs, speed, capacity, and scalability improvements are expected, although producing such chips is still a significant technical challenge. Areas of relevant research interest are improved optical signalling, neuromorphic photonics, opto-magnonics and topological photonics.

- **Improved Optical Signalling:** The movement of information across nodes constrains the benefits of increasingly distributed and parallel computing systems. Research is ongoing to develop new microelectronics, seamlessly integrating photonics with electronics, thereby improving by two orders of magnitude bandwidth, power efficiency, channel density, and link interconnectivity [153]. On an application-specific basis, this photonic input/output is being explored for field-programmable gate arrays (FPGAs) and other integrated circuits used extensively in sensor, and RF systems [153].

- **Neuromorphic Photonics:** Using biomimetic neuromorphic photonic designs (e.g. computing with light), specialised AI/ML chips may be designed to significantly increase the efficiency and effectiveness of computational tasks such as image recognition, speech processing, machine learning, pattern matching etc. [121].

- **Optomagnonics:** Merges photon-spin coupling in solid-state systems via optical and microwave cavities. This mix of silicon photonics, electronics and spintronics [534] opens up many new applications in sensors and quantum computing, such as magnon-mediated microwave-to-optical transducers for quantum computing applications [535] or hybrid solid-state spintronic-photonic interconnections [536, 537].

- **Topological Photonics:** An evolving area of research is the use of geometric and topological concepts to design and control the behaviour of light [119, 538, 539]. Along with the discovery of topological insulators (e.g. materials that are insulators within their interiors but allow the flow of electrons along their surface), this has allowed for the manipulation and creation of new states of light with remarkable and potentially practical properties. These effects can be realised in crystals, metamaterials and quasicrystals [539].

Lasers also provide considerable technological surprises, especially as vital elements in photonics and communication. Significant developments in compact radiating photonics, nanolasers (lasers-on-chips), and SWaP-C developments on free-space optical lasers are a few areas to note.

- **Compact Radiating Photonics:** Research seeks to develop high-power high optical intensity lasers for directed energy effects suitable for mobile platforms (e.g. highly mobile autonomous systems). Integrated photonics and amplification techniques and innovative thermal management strategies are being explored [153] to solve the fundamental SWaP-C challenges.

- **Nanolasers (Lasers-on-Chip):** Efficient super-compact lasers are being actively developed, with an eye towards application in next-generation optical chips, optical computing systems, sensors, and communications. One such example [540, 541] exploits a super-efficient photonic crystal waveguide of remarkably small size relative to other approaches. Another DARPA project, Lasers for Universal Microscale Optical Systems (LUMOS) [153]), seeks to integrate laser sources into integrated silicon photonics - "lasers-on-a-chip". Such a package will enable compact and rugged systems for PNT, communications, 3D imaging, and quantum technologies.

- **Free-Space Optical:** Free-space optical systems generally rely on large, expensive and precise optical components, limiting their applicability in many use cases. However, research is underway by DARPA to address the SWaP-C and performance challenges, enabling expanded applications for Light Detection and Ranging (LiDAR), laser communications, laser illumination, navigation, and 3D imaging [153]. One example, another DARPA programme, is the Modular Optical Aperture Building Blocks (MOABB) programme, which is exploring the use of a scalable optical phased array system using millimetre-sized optical building blocks, thus enabling beam steering without mechanical components, a reduction in size and weight by potentially two orders of magnitude, and a three order of magnitude increase in steering rate.

Spectrum

The EM spectrum and associated communication modalities are at the centre of big data, enabling sensors and communication. Therefore, controlling the EM spectrum is a prerequisite to information dominance.

Electromagnetic dominance is the ability to use more of the spectrum, to share the spectrum more efficiently, to protect one's own forces' use, and to deny enemy use. The future will bring - among other things - faster, more reliable wireless/radio communications, electronic warfare resilience, secure streaming video, and a smaller deployed footprint. As a result, the EM spectrum is, and will continue to be, increasingly congested as both military and commercial systems via bandwidth. AI to support cognitive sensors (e.g. cognitive radars) and communications, which adjust agilely to maximise collection and through-put, will become essential to avoid conflict in the congested (and perhaps contested) EM spectrum. This will be especially essential for operations in urban environments with the most congested EM spectrum.

The electromagnetic spectrum is increasingly contested, congested and commercial [542]. The introduction of 5G and upcoming 6G technology is well-documented. This will form a core digital backbone for NATO military and enterprise activities. The associated competition and conflicting standards may result in even more intense pressure for commercial use of the available EM spectrum. Nevertheless, military success in theatre often depends on a force's ability to control and exploit the EM spectrum while, at the same time, denying hostile actors access to it.

By 2025, decoys will be able to obscure visual, thermal and radar wavebands and be an integrated part of defensive aids suites [2]. Having fleets of robotic decoys for deception operations should be technically possible. Meanwhile, simple decoys aimed at mimicking the electromagnetic signature of headquarters of manoeuvre units are more likely to be developed in the short term. Electromagnetic field-based stealth systems and broadcast electronic decoys hold promise for the defensive capabilities of future electrically powered systems.

The number of research activities in this area is extensive; however, a few emerging technological aspects are of particular interest:

- **Adaptive Camouflage:** Research in this area seeks to adapt the optical and near-optical signatures associated with a vehicle, person or facility so that the signature is like the existing background or surroundings. Such camouflage may span a variety of spectral bands. Adaptive camouflage seeks to dynamically change the signature simultaneously across multiple spectral bands, ranging from radar, IR, visible, and UV, to match movement or changes in the background. Research in this area aims to enable technologies that will support this adaptive behaviour, independently or under human control, while being robust to changes in other physical or technical parameters [42, 153]. This research includes developing bionic adaptive camouflage materials for visual stealth, quantum camouflage [543, 544, 545], and research on next-generation photonic crystal infrared materials [546].

- **High-Frequency High-Power Overmatch:** The development of high-power amplifiers tailored for high-frequency millimetre wave communications would open a portion of the EM spectrum that may be less crowded or contested. This would also support high-data-rate communications, increase sensitivity, and higher resolution for various sensors [42, 153].

- **Adaptive Spectrum Management:** Cognitive radios or sensors employ AI/ML algorithms to adapt to a changing EM environment, including jamming and increased commercial use. They support more effective and agile use of the available spectrum. Applications extend from radar, signals intelligence, electronic warfare, and communications. Such techniques are not new but technological improvements across the hardware and software spectrum, especially in AI/ML, have allowed increasingly more effective and hitherto unachievable techniques to be employed [547, 548, 549, 550].

- **New semiconductors**, materials, AI/ML, and analytics-driven advances in signal processing [210]. This can support increased manoeuvre in the EM spectrum for tactical purposes through improvements to filtering, surveillance, and localisation [210].

Directed Energy Weapons

The recognition that non-kinetic conflict is essential to effects-based warfare is growing [551]. While not a new technology, directed energy weapons (DEW) have significantly matured, and demand has surged globally. These lasers and high-power microwave weapons are already being seen to be a disruptive force on the battlefield and are expected to be even more widely used over the next few years [63, 556, 557, 558, 559, 74, 551, 560, 561, 552, 553, 554, 555]. Estimates are that the current DEW global market is USD 14.3 billion, growing to USD 72.1 billion by 2027 [562]. In no small measure, this growth is being driven by improvements in energy storage, AI/ML, and Materials. In addition, many DEW systems have become operationalised or are at very high TRL levels. The value of such systems and the continuing technical challenges were explicitly noted and played during recent STO technology watch tabletop exercises and serious games.

Military Implications

BLUE

Electronic warfare (EW) uses electronic technology to detect, intercept, jam, or mislead electronic communications from opponent forces [563]. It is a tactic of warfare that employs electronic means to disrupt adversary systems such as radar and communication networks. EW can also be utilised to guard against electronic attacks on friendly systems. The purpose of EW is to disrupt or degrade the enemy's capacity to use electronic systems while defending friendly systems from analogous threats. Future deployment scenarios will necessarily require a large range of responsibilities and basic functions, such as intelligence, surveillance, and reconnaissance (ISR) operations, tracking, electronic support measures (ESM) and electronic countermeasures (ECM) for EW, and Network Centric Operations (NCO), including High Data Rate Links Beyond Line of Sight. As non-kinetic conflict is growing [551], EW is undergoing a reinvigoration [564] driven by military forces' increasingly sizeable electromagnetic signature [565]. As such, the value of EW as a weapon and the need for sensing and protection are growing. As a result, innovation is occurring, and the DARPA Non-Kinetic Effects (NKE) programme is an example where the value of EW in force-on-force conflict is being recognised and enabling technologies are being developed [153].

Enable

- **Cognitive Electronic Warfare:** Emerging tactical communications and radar systems with flexible software-defined radios (SDRs) and configurable Radio Frequency (RF) front-ends enable these systems to conduct extremely reactive and adaptive electronic defence. This is because many EW systems are trained on known communications and radar modes of operation, but SDRs may be swiftly updated and deployed with previously unseen modes of operation. Considering the accelerated pace at which software and firmware upgrades may be implemented, the development and deployment of EW systems capable of reacting to unexpected modes of operation in the theatre of conflict effectively and decisively is required. The likelihood that threat systems coordinate with one another for increased situational awareness, tracking, and target engagement complicates the picture even further.

- **Airborne and ground-based systems for communication:** The application of such multipurpose common hardware necessitates the development of new operational ideas, systems, and components. The improved performance, versatility, and agility of completely digital RF systems enable RF spectrum supremacy and assure continuous real-time communications, situational awareness, signal identification, and the deployment of electronic defence and assault systems. Another advantage is the potential to deny opponents access to the spectrum, restricting their capacity to operate, attack, or retaliate during a conflict. Almost all wireless operations of ground, naval, or aerial systems may be operated as software-defined solutions in conjunction with antenna function sharing (e.g. electronically scanned), including:

  - High-capacity, reliable, and secure communication and data link connections to meet the tactical field communication needs of the military covering all relevant frequency bands;
  - Detection and surveillance in Air-to-Air and Air-to-Ground, or volume and surface search including respective target tracking, reconnaissance, and classification of fixed targets using synthetic aperture radar (SAR) operation in Spot and Strip mode;
  - Electronic Support Measures (ESM) to rapidly detect, intercept, identify, and track electromagnetic energy sources to recognise threats, collect targeting and signals intelligence data, and inform future operational planning;
  - Electronic Protection (EP) for safeguarding human resources, facilities, and equipment against the effects of an electronic attack by hostile forces that could neutralise or destroy its combat capabilities;
  - Use of electromagnetic or directed energy for Electronic Attack (EA) to assault enemy forces' electronic infrastructure with the intent to degrade or eliminate their combat capabilities; and
  - Integrated Electronic Mission Support (EMS), as well as communications intelligence (COMINT) operations, gathered from the communications of individuals, including various types of interactions.

- **Electromagnetic metasurfaces:** Soon, we can expect phased arrays that can be made conformal to vehicles and steer high-gain beams within a limited sector [566]. This technology is beneficial for nose-radar for fighter aircraft, high-resolution synthetic aperture radar (SAR), and Satcom on-the-move systems for small terrain vehicles.

Prepare

Cognitive radar: Cognitive radar (CR) will be a game changer in military scenarios where the spectrum is heavily congested and contested, with a significant impact on electronic warfare (EW). CR will be able to elude EW systems and outperform current radar technology in detecting, tracking, and imaging challenging targets. This technology must also be tracked as potentially dangerous if in the hand of red forces as it may bring an advantage in support for adversarial ISR operations [567].

Protect

As anticipated in the previous iteration of this report, S&T Trends 2020-2040 [2], decoys can now be a seamless component of defensive assistance suites and can be used to mask optical, thermal, and radar wavebands. Technically speaking, fleets of robotic decoys for deception operations should be feasible. Still, in the near future, simple decoys designed to replicate the electromagnetic signature of headquarters of manoeuvre units are more likely to be produced. In addition, future electrically driven devices may be able to defend themselves using electromagnetic field-based stealth techniques and disseminate electronic decoys.

Electronic Countermeasures (ECM): Depending on their degree of autonomy, UAVs may rely on satellite navigation and high-frequency (HF) communications. Today, many small UAVs still use the Global Navigation Satellite System (GNSS) for navigation, but visual electro-optical (EO) navigation methods are rapidly improving. Larger, more advanced UAVs are self-sufficient when it comes to navigation. However, eliminating civil and military satellite navigation systems in the field severely limits UAV systems that rely on GNSS's free and open operation. Instead, less autonomous vehicles and platforms transmitting sensor data use RF communication links between the aircraft and the control station, directly or through ground, air, or space infrastructure. RF communications can also coordinate the individual UAVs that make up a swarm. These connections typically transfer control information to the UAV and coordinate between individual nodes and sensor data back to the control station. In principle, these can be thwarted using electronic countermeasures. However, this is not an easy task, as the connection is probably robust and designed for small signatures with a low probability of detection/interception (LPD/LPI). To effectively break such connections, ideally, the communication should be detectable. However, a priori knowledge of the frequency bands in which current systems operate allows for less effective barrage jamming.

Sustain

- **High-resolution targeting** [568] is reachable by compressed digital holography producing very high-resolution images for long-range target identification. Such images allow estimation of target position and velocity, penetrating both camouflage and foliage. In addition to visual markings, coherent optical detection can also be used to measure vibrations to disentangle decoys and assess the damage on the battlefield. Similarly, messy field data can be used to correct atmospheric aberrations and extend the working range of the sensor. Compared to passive visible imaging, active optical sensors such as Short Wavelength Infrared (SWIR) LiDAR offer more opportunities for noise reduction through phase-error correction algorithms, offering the advantage of day and night imaging. Additionally, these LiDARs have higher resolution than long wavelength sensors such as Medium Wavelength Infrared (MWIR), Long Wavelength Infrared (LWIR), or HF imagers [569]; due to the low illumination, LiDAR is less likely to be intercepted than active radar, allowing for covert operations; and the short range and bandwidth of LiDAR transceivers make them less susceptible to interference.

- **Electronic support measures (ESM):** For electronic support (ES) sensors to detect and locate a platform, the platform must emit energy in the electromagnetic spectrum. Autonomy levels vary widely from cheap commercial drones to military UAVs. Some UAVs have some form of data link to remotely control the platform, transmit real-time sensor data, or enable communication between swarms of UAVs. These emitters are often low-power and may have directional antennas for both stealth and range purposes. For these reasons, various anti-UAV ESM sensors are optimised for detecting low-power and standard civil UAV radio link protocols. Others allow users to implement their custom filters or other forms of detailed descriptions of signals of interest. ESM sensors help detect, track and identify UAVs. However, as more autonomous platforms are expected, these sensors will gradually become less contributory over time.

- **Ultra-wide bandgap (UWBG) semiconductors for next-generation RF and power electronics:** If successfully applied to devices, UWBG semiconductors have the potential to improve RF power density by a factor of 3 to 10 over gallium nitride (GaN). Assuming thermal management is not the fundamental limiting factor, the military would benefit if higher radiated power could be achieved from a phased array of the same size as a GaN-based phased array or if the same radiated power could be achieved from a smaller phased array. This provides system advantages for radar, electronic warfare, and communications. In addition, depending on the details of the degradation physics of UWBG semiconductor devices, this technology may operate at elevated temperatures, reducing the requirements for cooling support infrastructure. Finally, UWBG devices can operate at higher voltages. This reduces the need for inefficient, bulky and heavy DC/DC converters to step down bus rail voltages (100-1000 volts) to transistor voltages (10 volts).

RED

Overall, the benefits of RED are similar to those available to BLUE, even if the assumption does not consider potential asymmetries between RED and BLUE (e.g. access to resources, human capital, etc.).

Worth mentioning is how emerging technologies may considerably extend troop capabilities while presenting hazards associated with overdependence, such as the inability to preserve technology-supported skills and capacities [570]. For example, while personal electronics are powerful tools, troops must also be prepared to lose their capabilities in isolated or electronic warfare scenarios suddenly. The disadvantage would be exacerbated in combat against a technologically illiterate - or any - opponent who has been taught to function in low-power, low-communications conditions (e.g. wayfinding skills).

Additionally, adversaries' use of **Machine Learning and Artificial Intelligence for RF-sensor technology** is mostly open-source and freely available to improve the signal processing chain and upgrade existing radar- and EW systems in a very cost-effective manner [571]. Realistic RF signatures can potentially be created without requiring real measurements of blue force targets [572], using EM-simulation and generative adversarial networks (GANs). Counter-AI methods can be applied to deceive machine-learning methods applied on the blue side, e.g. for electronic warfare purposes (see also A). E&EM cognitive abilities rely on developing ML/AI methods largely driven by private industry and civilian applications. The proliferation of this technology and deep learning frameworks is not restricted and can be easily used by adversarial government actors or even terrorists without large investments. For blue force development, it is important to foster large-scale data collection campaigns, including ground-truth tagging of the data and making it available to research institutions. Also, the rules of operation, procedures and policies must be adjusted to deploy ML/AI methods operationally. Formal qualification and certification guidelines must be developed for defence companies to invest in and develop ML/AI-enhanced products.

Interoperability

Interoperability of futuristic, complex and articulated deployment scenarios demands a conspicuous number of roles and tasks (e.g. ISR-OPS, tracking, electronic support and countermeasures for EW and network-centric operations - including High Data Rate Links Beyond Line of Sight (LOS), Data Links Beyond Line of Sight (BLOS)) in order to satisfy the military appetite for hardware systems for communication, sensors and alternative wireless services. Combining these Radar, EW and COMMs functionalities in one fully-digital RF system will provide reduced payload integration volume and weight and enhancements of system interoperability and efficiency through optimised use of frequency bands and aligned sensor response time.

S&T Development

This section addresses the state and rate of development of science in the Electronics and Electromagnetics fields. Further, it answers the question: What does E&EM mean for developing related scientific areas, or what synergistic relationship does it have with these NATO S&T Priorities?

State of Development

AI

Using AI on sensors to pre-process information and provide adaptive use of frequencies (e.g. cognitive radar [573]) and bandwidth will paradoxically lead to decreased communication traffic. Additionally, **Machine Learning and Artificial Intelligence for RF-sensor/sensing technology** [574] will improve the target detection, tracking, and recognition capabilities of radar and electronic warfare systems [575]. As software and signal-processing methods, they can be applied to upgrade existing hardware. Self-learning and cognitive radar systems are conceptually a new class of multi-functional RF systems that require software-defined radio hardware, waveform agility, and a system architecture based on the perception-action cycle. These systems will further increase the RF-sensor performance and allow for a higher level of automation.

Data

See D.

Space

See J.

Quantum

Quantum radar has the potential to make stealth technologies obsolete, provide more accurate target identification, and allow covert detection and surveillance [576].

Biotechnology

To note interesting advancements in the field of electro-mechanical biotech and development in organic solar cells [577].

Materials

The wide range of novel electrical and electromagnetic materials enable technological solutions such as solar cells, sensors, photoconductors, carbon nanotubes, graphene, thermoelectric materials, and meta-materials [577] while promising research advancements in photoconductivity in materials, temperature-insensitive bandgap III-V, graphene, materials for terahertz engineering, metamaterials, thermoelectric materials, transparent conductive oxides, and inorganic perovskite oxides[577]. Furthermore, **Ultra-wide bandgap semiconductors for next-generation RF and power electronics** breakthroughs in developing wide bandgap (WBG) semiconductors such as SiC and GaN have made tremendous impacts on the commercial and military sectors. From optoelectronics for solid-state lighting to power electronics for power conversion and radio-frequency (RF) transistors for mobile phone base stations, WBG semiconductor materials have contributed to advances in energy efficiency and connectivity. All of these technologies are assessed at TRL 1-3. The research community is aware of the potential of these materials and is actively trying to make a breakthrough that will lead to further TRL development. It is possible that one of these materials could advance quickly to TRL 6+ in the short term. If there is a sustained investment, some of these materials (or others not yet found) should be capable of reaching TRL 6 within 8-20 years. Advancement in UWBG semiconductors and devices should lead to the eventual replacement of silicon (SiC) and gallium nitride (GaN) electronics in RF and power applications. This will realistically take more than 20 years to occur.

Energy

Electromagnetic metasurfaces [578, 579, 566] are expected to deliver in the short Term (0-7 years) TRL 4-5 multi-layered metasurface based wide band antennas solution with higher integration of electronics, metasurface based conformal antenna arrays, and metasurface based Electronically Scanned Arrays (AESA) with high electronic integration. In the long run, metasurface-based Electronically Scanned Array (AESA) solutions with multiple steerable beams in different directions will emerge at TRL 3 (8-20 years). Whereas, the transposition of the technology to optics is expected in the longer-term (21+ years) at low TRL.

STO Activities

Several STO Scientific and Technical Committees have produced significant research on EM technologies. Many panels have ongoing activities on several topics aligned with these technologies. The following is a sample of ongoing activities:

- AVT-344 Assessment of Micro Technologies for Air and Space Propulsion
- AVT-371 Materials and technologies for electro-optical camouflage (Cross-Panel)
- IST-181 (COM) Terahertz-band Communications and Networking
- MSG-181 Physics-Based Electro-Optic/Infrared Simulations – Best Practice Recommendations for Decision Support
- SAS-140 Directed Energy Weapons Concepts and Employment
- SCI-304 Optimised and Reconfigurable Antennas for Future Vehicle Electronic Counter Measures
- SCI-316 High Energy Laser Weapons: Quantifying the Impact of Atmospherics and Reflections
- SCI-326 Electronic Support (ES) Techniques Enabling Cognitive Electronic Warfare (EW)
- SCI-332 Radio Frequency-based Electronic Attack to Modern Radar
- SCI-340 HEL Weapon Technology, Opportunities, and Challenges
- SCI-348 Real-time Coalition Electromagnetic Battle Management (EMBM)
- SCI-SET-323 Above Water EO/IR Signature Requirements from an Operational Perspective
- SET-246 Short Wave Infrared Technology: a standardised irradiance measurement and compatibility model to evaluate reflective band systems
- SET-249 Laser Eye Dazzle Threat Evaluation and Impact on Human Performance
- SET-269 EO/IR Ship Signature Dynamics
- SET-285 Multifunction RF Systems
- SET-286 Acoustic and Seismic Sensing of Threats in Urban Environments
- SET-293 RF Sensing for Space Situational Awareness
- SET-294 Advanced Mid-Infrared Laser Technology
- SET-295 Radar Signature Measurements of Maritime Platforms
- SET-298 Electronic Attack and Protection for Modern Active/Passive Netted Radars
- SET-302 Cognitive Radar
- SET-303 Military Applications of Extreme Laser Fields
- SET-308 Trends in Ultrashort Pulse Laser Source Technology Improvements
- SET-316 Realistic Trace Explosives Test Standards for Evaluation of Optical Sensors in Relevant Scenarios
- SET-318 AI/ML and Cognitive Radar
- SET-323 Advanced Methods for Laser Dazzle Evaluation
- SET-325 Shortwave Infrared Technology: Irradiance Measurements to Evaluate Reflective Band Systems

Scientometric Analysis

Keywords associated with Electronics and Electromagnetics (E&EM) as derived from STEAM analysis are shown in Figure E.1.

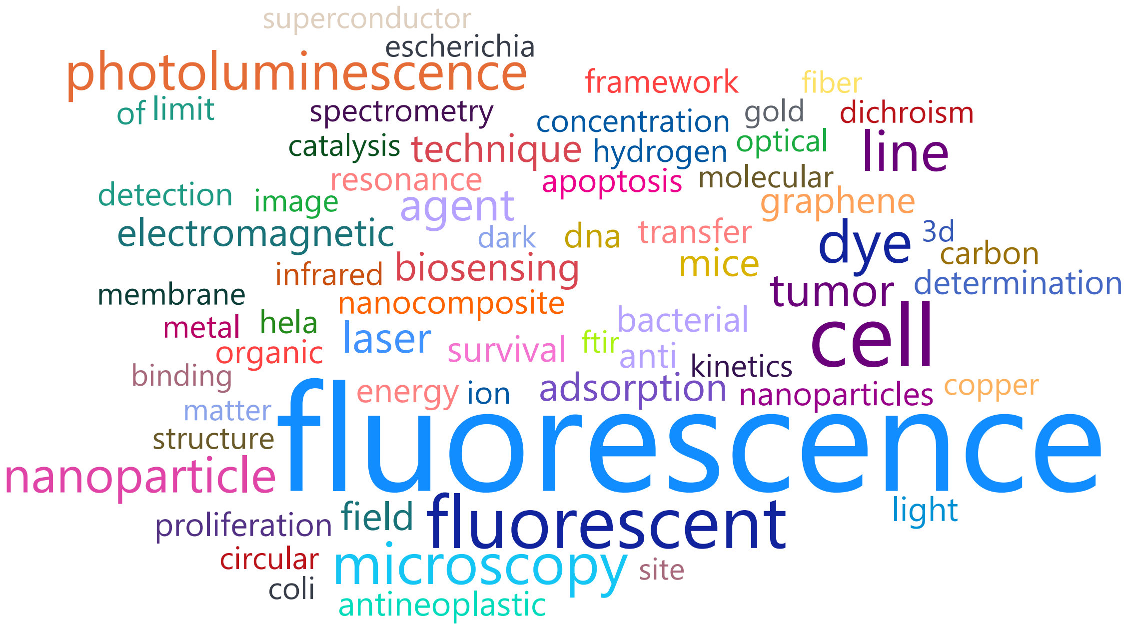


Figure E.1: *STEAM - Electronics and Electromagnetics - Keywords*

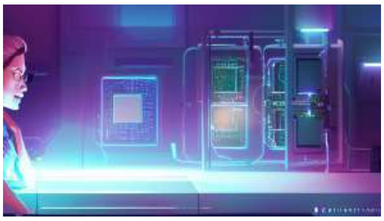
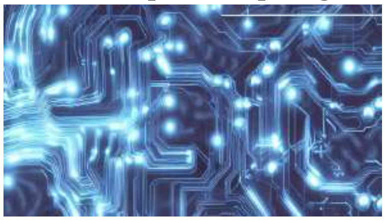
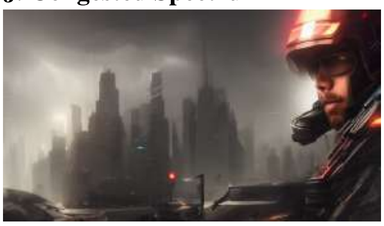
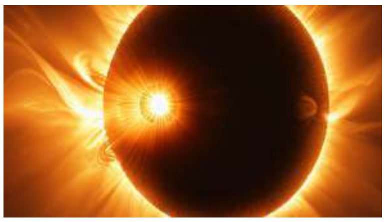
Survey Results

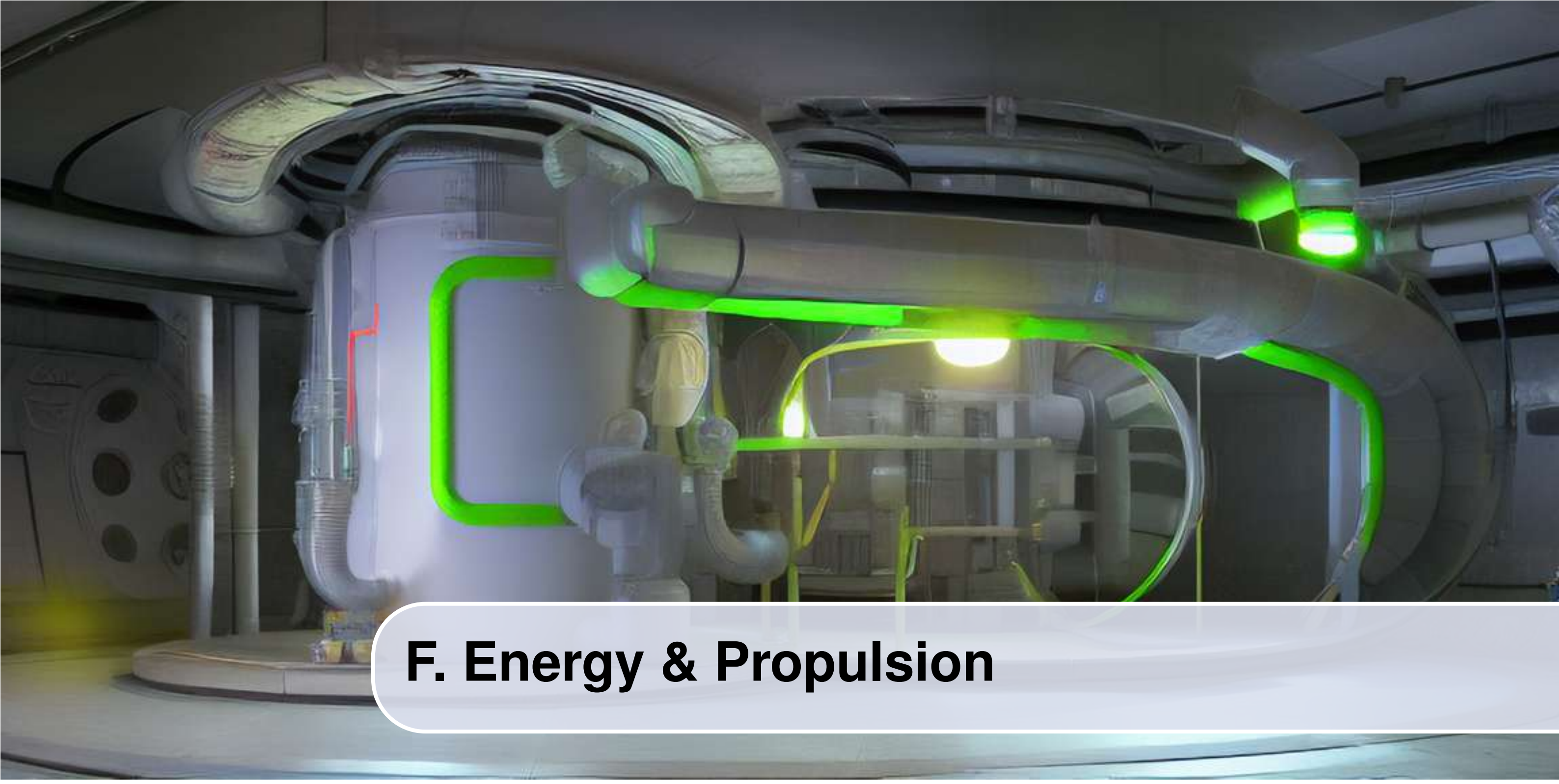
The following table presents the assessed potential impact, state and rate of development and identifies areas for focused research.

Table E.1: *Electronics & Electromagnetics (E&EM) 2023 - 2043.*

EDT	Technology Focus Areas	Impact	TRL	Horizon
E&EM	Antennas	High	9	2022-2025
	Directed Energy Weapons	High	5-6	2030-2035
	Microelectronics	High	9	2022-2025
	Photonics & Lasers	High	7-8	2025-2030
	Spectrum & Signature Management	High	5-6	2025-2030

Conjecture Card: Electromagnetics and Electronics

A. Stealth  Active manipulation of electromagnetic fields leads to broad-spectrum stealth for soldiers and weapon systems.	**B. Non-Silicon Semiconductors**  New non-silicon materials enable next-generation semiconductors to reduce power and size while improving performance.	**C. Smart Grid**  An AI-enabled high-voltage transmission grid reduces loss and enables next-generation energy generation capabilities.
D. Photonics  Light-based processors (i.e., photonics) greatly improve the power, size and performance of next-generation electronic systems.	**E. Quantum**  New semi-conductor-based spin qubits enable the development of minimized room temperature quantum computers and co-processors.	**F. Neuromorphic Computing**  Electronic devices and algorithms directly mimicking the human nervous system and brain provide a substantial leap in computational capabilities, especially for AI applications.
G. Cognitive Spectrum Management  Using AI enables agile use of the limited and crowded electromagnetic spectrum.	**H. Terahertz and Femtosecond Lasers**  New on-silicon terahertz emissions and femtosecond laser generation and detection systems allow new scientific and technological applications, especially in studying biological processes.	**I. Wireless Power Transfer**  Developments in wireless power transfer allow cost-effective exploitation of space-based solar collection systems, microwaving power from collection satellites to local ground stations.
J. Congested Spectrum  Extensive commercial use of available spectrum, national interoperability issues and competing technical standards severely impede operational communication.	**K. AI-Enabled EW**  New agile Cognitive Electronic Warfare (CEW) systems cause severe degradation of Alliance theatre-level operations.	**L. EMP / Solar Storm**  An electromotive pulse (nuclear) or solar storm causing geomagnetic induced currents severely degrades Alliance military and civil communication and power systems.



F. Energy & Propulsion

Energy & Propulsion
Energy is the lifeblood of our warfighting capabilities - General David Petraeus [553]

Definition

Energy & Propulsion
Energy storage and conversion technologies offer ways of harnessing energy from one source and in one form and preserving it for later use or altering it into another form. This can involve established technologies to harness power from the environment like fossil fuels, nuclear power, renewables, or energy storage, usually via batteries. We are also starting to see novel ways of gathering and storing energy, including next-generation batteries and fuel cells [580].

Keywords

Batteries · *Energy Storage* · *Nuclear* · *Renewables* · *Propulsion* · *Micro-grids* · *Capacitors* · *Electrification* · *Fission* · *Green* · *Transmission* · *Hybrid*

Developments

Overview

Energy considerations have civilian and military implications and are marked by the energy trilemma, which combines economic objectives, environmental concerns, and energy security [581]. Traditionally, military operations are energy intensive and heavily reliant on fossil fuels [582]. Thus access to energy has historically been of the utmost importance for strategic purposes as it can act as an enabler or a weapon of war [581]. In 2021, all NATO Allies combined represented almost 30% of the global primary energy demand (i.e.commercially traded fuels, including modern renewables used to generate electricity) [583], and in 2019 they produced 25% of the global energy supply [584]. Major trends regarding energy consumption indicate that the worldwide energy demand will grow by at least 15% [585, 586, 587] in the next 30 years. This increase is expected to be accompanied by a global reduction of carbon dioxide (CO_2) emissions from NATO Allies and NATO itself, which has announced to reduce CO_2 emissions by NATO bodies and commands by at least 45% by 2030, down to Net Zero Emissions (NZE) by 2050. This ambitious objective will be accomplished through implementing "clean energy" policies, changes in human behaviour, and developing new technologies.

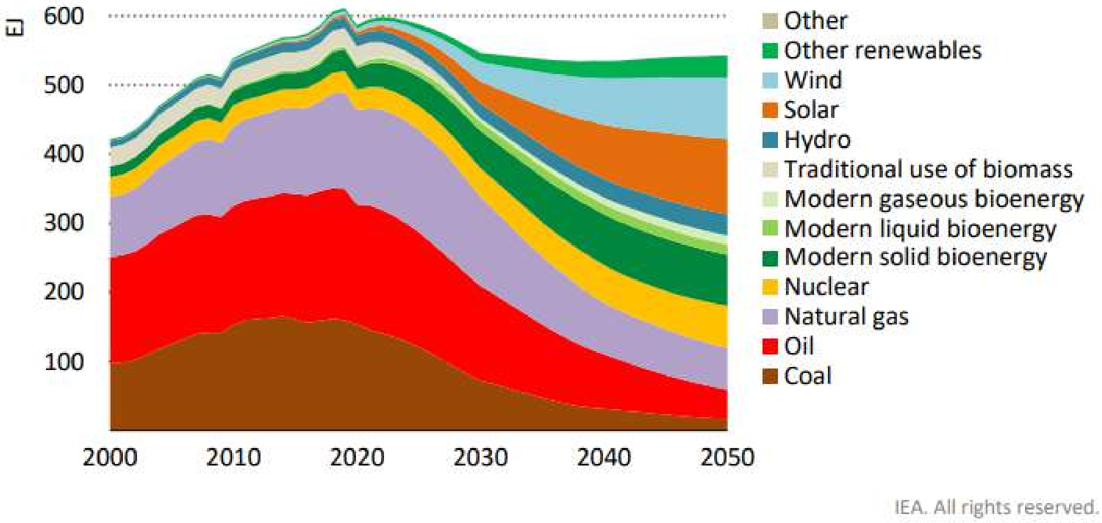


Figure F.1: *Total Energy Supply in the NZE (CREDIT: [588])*

At the same time, the global energy crisis caused by Russia's invasion of Ukraine is disrupting the Allies' traditional energy supplies. It reinforces the importance of securing alternative energy sources. At the 2022 Madrid Summit, NATO adopted its new Strategic Concept, which considers the role of energy security in a more challenging strategic environment, as authoritarian actors and strategic competitors conduct malicious activities in cyberspace, manipulate energy supplies, and employ economic coercion. As a result, Allies agreed to enhance their energy security and invest in a stable and reliable energy supply, suppliers and sources [589]. However, the new clean energy transition through the shift from fossil fuels to more sustainable energy sources (See: F.1) will raise other energy security concerns such as access to strategic minerals which are needed for producing batteries and other energy storage devices.

All of the previous factors make it clear that mastering new energy and boosting clean energy innovation will be required to achieve the objectives mentioned above [588]. Generally, research of interest to NATO in this area is concentrated in the following areas:

Power Generation

Clean energy generation will be essential if NATO achieves its ambitious climate change objectives. Unfortunately, research in this area is not particularly focused on military applications. Nevertheless, emergent research topics of potential interest to NATO are nuclear energy, renewable energies, non-conventional fuels, and other hybrid energy sources. In addition, artificial Intelligence and Machine Learning techniques will empower a major leap in efficiency.

In recent years, **nuclear** power, particularly fission, has developed a strong negative reputation. However, the recent disruption of gas supplies to some NATO Allies is breaking some of the taboos around nuclear energy sources. Some Allies have recently declared nuclear as a sustainable or 'green' energy source to attract more private investment into this technology [590]. Also, the International Energy Agency (IEA) acknowledges that nuclear power will support the energy goals set by the international community in recent years [591]. In fact, in the next 15 years, China is expected to invest $440 Billion (USD) in such technologies to move away from coal-fired electricity [592]. Some claim that the European Union (EU) will have to spend EUR500 Billion by 2050 in nuclear energy to achieve its goal of carbon neutrality [593]. Thus, relevant research will continue in nuclear energy-enabling technologies in the upcoming years to develop safer and more deployable systems. For example, thorium-based molten salt reactors (MSR) [594, 595, 596] hold the promise of being safer and greener than traditional uranium-powered reactors, as well as presenting fewer nuclear proliferation risks. Accident-tolerant nuclear fuels may [119] also provide a safer path for large-scale future use of nuclear power. On a smaller scale, small nuclear reactors (SMR) [597, 598, 599, 600, 601, 602] are being developed to enable microreactors on military bases, support extra-terrestrial (moon, mars) habitation, as well as nuclear thermal propulsion (NTP) for space exploration. At the same time, it seems that the forever-lasting pursuit of nuclear fusion is regaining momentum [603]. Indeed, breakthroughs in constructing viable reactors [604] and applying novel algorithms to control elevated plasma temperatures [605] offer some optimistic prospects for its commercial deployment sometime in the next twenty years. Nevertheless, scientists must overcome considerable barriers to achieve break-even and gain [606, 607].

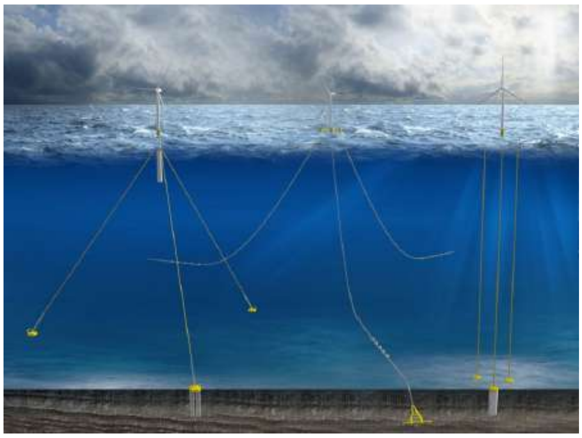


Figure F.2: *Wind Platform Offshore Mooring (CREDIT: US Department of Energy)*

Renewable energy sources are also another key element to achieve energy security, support military operations and mitigate the impact of climate change in the upcoming years. Out of all the renewable energy sources, in the Net Zero Emission (NZE) scenario, wind and solar are expected to have an eight-fold increase in renewable generation by 2050 [588]. However, solar efficiency and effectiveness improvements are being driven down yearly to the point where they are now competitive with fossil fuels [608]. Relevant research has focused on reducing production costs as well as increasing efficiency. Of interest are thin-film flexible solar cells [609], including non-fullerene organics [610], useful for wearables, clothing and windows. At the same time, there is ongoing research regarding the uses of solar energy in the space domain. This research includes projects to develop Space-based solar plants which will collect solar energy and send it back to earth via microwave beams [611]. Next-generation wind technologies seek to build more cost-effective turbines, advance mooring and anchoring technologies and develop flying platforms. The last two will allow the positioning of floating support structures over deep waters, unharnessing new energy generation potential above the sea. At the same time, major R&D on turbine development for thermal power plants (fossil fuel, solar thermal, or nuclear) will allow for increasing the efficiency of already existing systems [612].

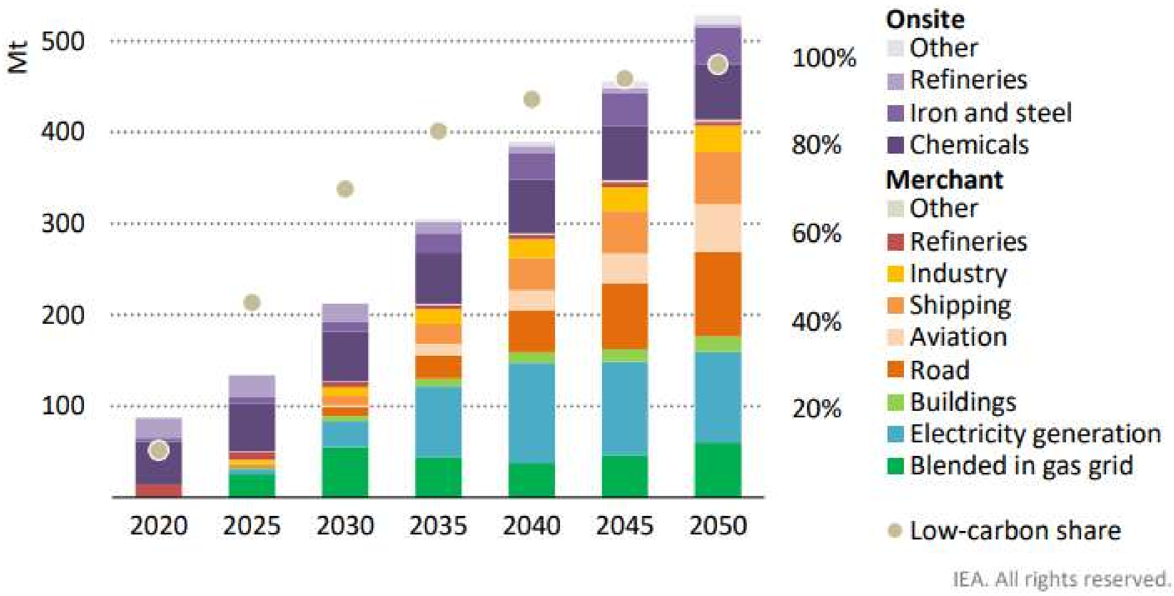


Figure F.3: *Global hydrogen and hydrogen-based fuel use in the NZE (CREDIT: [588])*

Research on **non-conventional fuels** is also in the spotlight. Bio-fuels provide a rapid and low operational impact by leveraging existing fossil fuel infrastructure and engineering with sustainable, carbon-neutral fuel. Biofuels (including bioethanol, biodiesel and biobutanol) [613, 614] may be produced from a variety of sources, including cooking oils, cellulose, algae, kelp, insects and alternative crops. Some promising approaches are black soldier fly larvae biodiesels, which employ larvae to convert organic wastes to larval fats, which in turn may be used to create biodiesels [119, 615]; or cellulosic sugars from sources such as agricultural waste and residues. Research challenges, in general, are focused on addressing the many disadvantages of biofuels, such as costs, environmental damage, water use, land use, fuel quality and employment in existing systems. New methods to obtain hydrogen without fossil fuels also show potential [616] to reduce CO2 emissions. In fact, according to the IEA estimates, the production and use of low-carbon hydrogen fuels will need to expand from 10% in 2020 to 30% in 2030 to achieve the 2050 NZE goal (See: F.3). Finally, the CO2 captured by carbon capture, utilisation, and storage (CCUS) technologies such as 'artificial leaf' technology may be employed to produce liquid fuels such as aviation or shipping fuels [617, 618].

Batteries and Energy Storage

The growing reliance on intermittent renewable energy sources and the electrification of the vehicle industry will require the use of **energy storage systems** with higher energy densities to improve power system reliability, flexibility, and security; and to power vehicles such as long-haul trucks or electric aeroplanes (See F.4). The areas of interest to NATO include improving battery management systems and innovative system approaches (including hybrid technologies) to increase the lifetime of the batteries (high number of cycles and calendar life) and research for the new generation of supercapacitors.

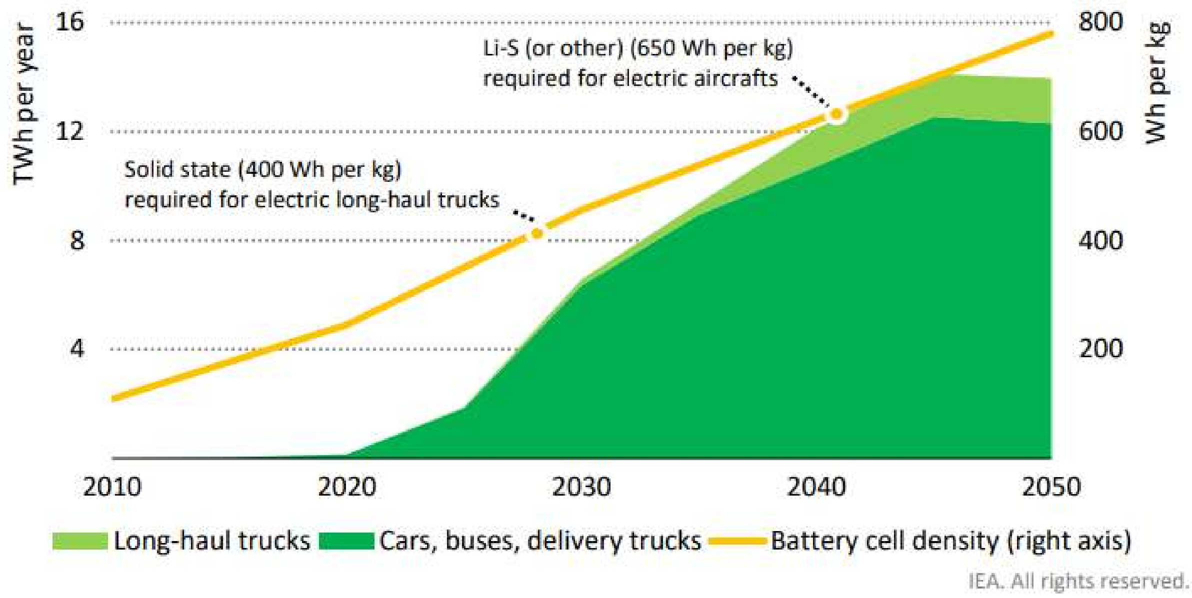


Figure F.4: Battery Demand Growth in Transport and Battery Energy Density in the NZE (CREDIT: [588])

Technological limitations and an ever-increasing demand for greater power and energy densities are driving the exploration of new **electrochemical energy storage** technologies. *Lithium-ion batteries* (Li-ion) have dominated the battery market since the late twentieth century due to their high gravimetric and volumetric capacity and good energy efficiency. In the upcoming years' Li-ion batteries may be enhanced through quantum simulations, which will allow predicting the behaviour of the battery components in advance [619]. Nevertheless, their multiple downsides (e.g. environmental damage, life-cycle, density, accidental fires, etc.) and technical limitations [620] favour their replacement by other battery technologies showing more promising potential. *Lithium-sulphur and sodium-ion* batteries may offer a solution to battery degradation and a higher battery density than Li-ion batteries but further experimentation is needed

[621, 622]. Aluminium battery technologies such as *Aluminium-air batteries* or *Aqueous Aluminium-Ion Battery* [623] seem a promising energy source for Electric Vehicles (EV) because of the abundance of raw materials and their high theoretical energy density [624] which will allow EV to travel distances up to 8,000 Km and then swap the empty battery with a full one in a short period of time. Nevertheless, these batteries are still expensive and carry some environmental problems. *Magnesium-sulphur* batteries also offer high energy density but lack good energy efficiency or cycle life [625]. Compared to batteries used in portable electronics or electric vehicles, wherein energy density and safety are the main concerns, batteries for grid energy storage need to be low-cost and durable to deliver a cost advantage through the years. Concerning this metric, room-temperature sodium–sulfur batteries also provide a greater advantage than lithium-ion batteries and are thus widely used in the grid for load-levelling applications. Other emerging battery technologies include dual-carbon [626], lithium-CO2 [627], lithium-metal [628], magnesium-metal, magnesium-sulphur [625], potassium-ion [629], potassium-metal, sodium-metal [630], sodium-CO2, zinc-ion [631], or zinc-CO2.

Electrical energy storage technology such as *Supercapacitors or ultracapacitors*, which do not rely on chemical reactions to release energy, provides another option for energy storage, with significant advantages in weight, safety, life, energy density, charging speed and toxicity [632]. Nevertheless, current technological limitations prohibit their general use [633]. A promising hybrid approach is supercapattery, which combines electrochemical energy storage with supercapacitors [121, 634]. This new technology will offer higher energy density than supercapacitors and higher power capability than batteries [635], offering a valid alternative to fossil fuels.

Power Transmission

Power, once generated, needs to be transmitted and distributed to the end users. Power distribution refers to all the hardware and cabling linking power sources to users. In the upcoming years, the clean energy transition scenario will incentive the expansion of the existent power grid [227] to adapt it to the specific needs of renewable energy production such as remote locations (e.g. offshore wind farms) or new suitable renewable energy generation locations where the current transfer capacity is low. At the same time, Energy supplies to the military must always be assured. Since the military depends on civilian energy networks, it is important to ensure the security of critical energy infrastructures and supply chains and develop innovative, resilient, efficient and autonomous energy solutions for the military, such as dedicated micro-grids with hybrid power generation. Microgrids are localised power grids able to disconnect from the larger transmission grids, thereby increasing resilience and localising power production [636]. One of the major research areas for microgrids is the technical challenge of coordination and synchronisation with the main grid or other microgrids [119]. In addition, hybrid and military microgrids (e.g. shipborne, mobile microgrids [637]) are sparking intense research interest due to their complex, and complicated nature [119, 638, 639, 640] and their potential benefits. Microgrids can be used as a climate change mitigation tactic in order to reduce military CO2 emissions; also, they enhance Allied resilience as they can island – or separate – if the main grid is attacked.

At the same time, research of interest to NATO is focused on meeting the power demands of modern battery-powered electronics. The demand for modern battery-powered electronics has driven research into wireless power transmission [119]. Areas of wireless power transfer of interest to NATO are:

- *Capacitive*: Used as a potentially lower cost and lightweight alternative to inductive power transfer. This technology offers improved performance and less energy loss [641].
- *Dynamic*: Charging on the move of electric vehicles allows for extended range, and reduced battery requirements [119], [642].
- *Underwater*: Wireless underwater power transfer has historically been difficult, but recent advances have increased transmission efficiency. Development of this technology would allow for such militarily relevant applications as wireless charging of underwater sensors, communications, and autonomous vehicles [119, 643, 644, 191].

- *Communication*: Wireless powered communication networking (WPCN) allows the battery of a wireless communication device to be charged via the power inherent in the communication signal [119, 645].

Propulsion and Vehicles

Today, oil is the main energy source for vehicle propulsion [618]. Nevertheless, petroleum products will be replaced in the upcoming years by more sustainable and low-carbon solutions (See: F.5) to meet the international community's ambitious goals. At the same time, by one estimate [646], the worldwide vehicle electrification market is expected to expand significantly in the upcoming years [647]. The military vehicle electrification market itself will grow from USD 4.8 billion (2020) to 17.6 billion (2030) [646]. The commercial movement towards electric vehicles is well placed to drive advances in batteries, motors and the AI/ML necessary to make this a reality. The utility of the Tesla cyber-truck or semi for military operations is self-evident; however, the production and technical challenges associated with delivering these vehicles in quantity should not be underestimated [648].

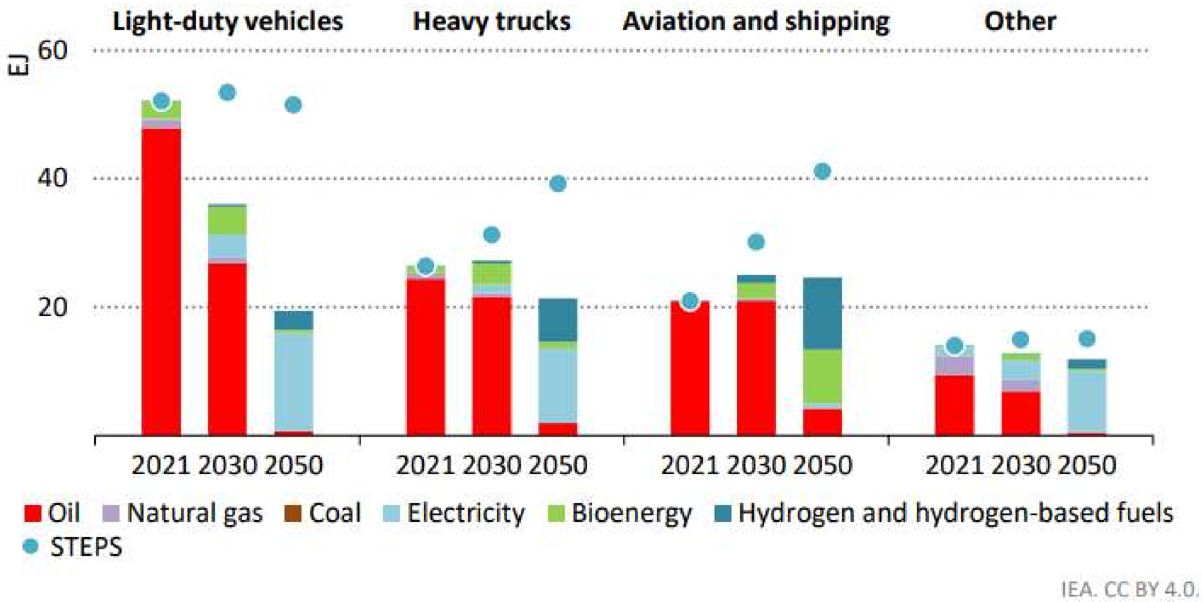


Figure F.5: *Final energy consumption in transport by source and mode in the NZE Scenario, 2021-2050 (CREDIT: [618])*

Military vehicles' propulsion or powering is a significant technical challenge but has been under rapid refinement and development for the last 300 years. However, from the perspective of this report, there are three crucial areas of development: electrification, novel aerospace engines and green operations. **Electrification** of military vehicles is very much at the early stages of development and faces considerable challenges [649]. Nevertheless, with the electrification of the civilian private and industrial transportation networks, it is only a matter before military vehicles move to electric propulsion. Electrification of aircraft is another hot area of research, with several commercial vendors having demonstrated significant prototypes and announced near-production ready aircraft [650, 651, 652, 653, 654, 655, 656]. Such electrification challenges are even more significant than those for land or naval vessels [650, 653]. In the short term, hybrid-electric or turbo-electric systems [657, 658, 659], along with fully electric turboprops and hydrogen planes [660, 661, 662] for short flights, hold the most promise [663]. Aircraft propulsion must be coupled with effective control surfaces and systems. Research is underway exploring the revolutionary improvements possible in in-flight performance using Active Flow Control (AFC). AFC technologies "alter the aerodynamic flow field thru ejection or suction of fluid via an orifice on a lifting body" [42].

In-Space Propulsion technologies (nuclear, chemical, solar or electric) are evolving rapidly in a search for cost reductions, increased endurance, reliability, and extended mission lengths. Propulsion options include:

- Nuclear thermal or fission propulsion (NTP): NTP technologies [664, 665] use a nuclear reactor to heat propellant.
- Nuclear fusion propulsion: This green technology is promising with significant venture capital investments but is also very early in development.
- Nuclear electric: A technology that uses ion thrust. Examples are iodine fuel electric thrust and water fuelled microwave electrothermal propulsion.
- Air Scooping electric propulsion (AESP): AESP, a very cutting-edge technology, scoops up sparse air molecules in the upper atmosphere for propellant, thus allowing low earth orbiting satellites to stay in orbit longer.
- Solar Sails: Exploiting pressure exerted by light on a large thin mylar sail in a manner analogous to a sailboat.

Combined cycle engines promise cost-effective human-crewed hypersonic flight (turbojet for low speed shifting to scramjet at high speeds). Research and development in this area continue and should be of interest given its apparent value for military operations [666, 667, 668, 669].

Military Implications

Figure F.6: *Mature solutions to support the US Army's "operational energy" (CREDIT: [670])*

Energy plays an important role in the common security of NATO Allies. The energy supply disruption could affect security within the societies of NATO members and partner countries. At the same time, energy is paramount for the armed forces. Energy considerations have long been essential to military operations to enable military capabilities and to project and sustain power. In the 2022 Strategic Concept, Allies agreed to invest in their ability to prepare for, deter and defend against the coercive use of political, economic, energy, and other hybrid tactics by states and non-state actors. At the Madrid Summit, the Allies also declared that they would strengthen their energy security and ensure reliable energy supplies to their military forces. In the years to come, NATO will continue to focus on assessing risks to Allies' energy security and deepen ties with other international organisations in this regard; regularly consult on energy developments with security implications to the Alliance; support critical energy infrastructure protection and resilience; explore innovative energy technologies such as micro-grids and synthetic fuels; continue to develop the military fuel supply chain; and adapt the military to the energy transition. Work on enhancing the resilience of energy, particularly electricity, and infrastructure, will also be given greater attention. With increased awareness of energy risks, enhanced capacity to support infrastructure protection, and a more energy-efficient military, NATO will be better prepared to respond to the security challenges of the 21st century.

BLUE

BLUE is currently heavily reliant on fossil fuels to sustain its armed forces [671, 672]. The energy consumption of BLUE forces surpasses the consumption of entire countries and usually represents the most intensive energy consumption within governments [582]. According to the European Defence Agency (EDA), 75% of the total energy consumption by EDA Member States Armed Forces' is covered by fuel oils and natural gas. At the same time, most NATO Allies are Net Energy Importers, and they are currently suffering increasing competition for the world's energy supply. In particular, Energy & Propulsion will impact the following operational and enterprise capabilities:

Enable

Maintaining a military force is resource intensive, and energy is of the utmost importance to ensure the production of military equipment and to enable military operations [673, 674]. Tactically viable alternative energy solutions to fossil fuels such as solar, wind, hybrid, nuclear, and biofuels for use at remote, austere locations can ultimately reduce the combat load and create a more agile and lethal force at lower cost and risk. This will support the needs of dispersed and highly mobile forces by enhancing the operational versatility of assets traditionally dependent on fossil fuels. Also, R&D on new propulsion systems and innovative energy supplies will be key to enabling military operations in more complex scenarios. New in-Space propulsion technologies will allow BLUE to conduct deep-space operations and translate into the extension of the life cycle of space systems.

Protect

Substituting fossil fuels with renewable energy sources can help reduce supply chain vulnerabilities [581]. Transport fuels account for over half of BLUE Forces' energy consumption [671]. The transition towards the electrification of military vehicles and energy production through renewable sources on-site will translate into a lower reliance on fossil fuels. Subsequently, reducing the number of military vehicles that need to be sent into high-risk military forward operations. Thus, minimising the exposure to the danger of troops [581]. Also, increased energy efficiency could offer combat power and agility benefits. In light of the global energy transition, NATO seeks to enhance energy efficiency and sustainability in the military while maintaining operational effectiveness.

Sustain

Energy supplies to the military must be ensured at all times. Since the military depends on civilian energy networks, it is important to ensure the security of critical energy infrastructures and supply chains and develop innovative, resilient, efficient and autonomous energy solutions for the military, such as dedicated micro-grids with hybrid power generation. In this regard, NATO's "Smart Energy" work focuses on reducing fossil fuel consumption in deployed force infrastructure (e.g. camps), resulting in more autonomy, a lesser logistical burden and a smaller environmental footprint. Allies are also reviewing the fuel supply chain, which includes the Central Europe Pipeline System, to ensure reliable energy supplies to NATO forces across the Alliance in a more demanding security environment. Furthermore, the advances in electronics, their miniaturisation and portability, and the development of economic renewable/green energy technologies offer significant opportunities. For example, innovative fuel cells will empower BLUE forces through advances in UAVs or the development of lighter and more portable military equipment. In addition, greener and low-emission energy technologies will reduce the "carbon military boot-print" [676] and improve the reliability and efficiency of electric power for mobile military camps.

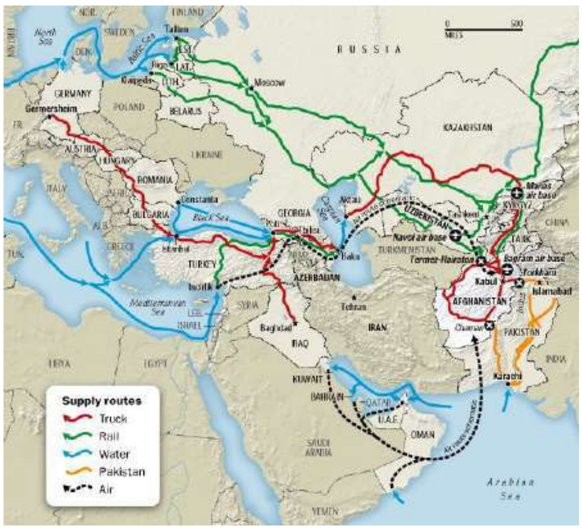


Figure F.7: *Northern Distribution Network (CREDIT: [675])*

RED

Historically, the energy sector has been repeatedly targeted by RED state, and non-state actors across the globe, including both the power grid and fuel distribution [677, 678]). BLUE's strategic competitors acknowledge the link between energy and military power projection. Russia's unprovoked invasion of Ukraine shows us the military implications of energy. On the one hand, Russia is targeting Ukraine's energy grid to cause social unrest among the Ukrainian population. On the other hand, Russia is aiming to gain political leverage through the weaponisation of energy [679] by withholding gas supplies [680] and exposing consumers to higher energy bills and supply shortages over the winter heating season.

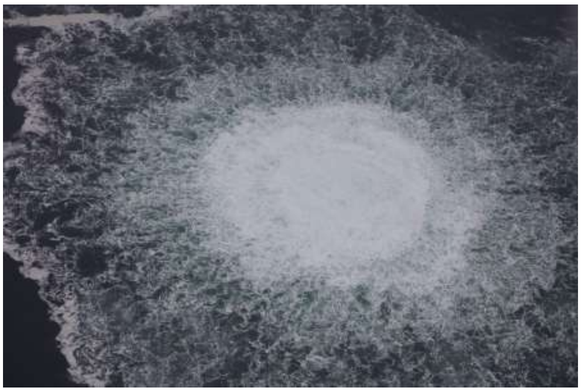


Figure F.8: *Nord Stream 2 leak in the Baltic Sea (CREDIT: Swedish Coast Guard)*

China's leadership in developing and deploying renewable energy sources such as offshore wind platforms, solar energy farms, and hydropower plants is already a reality [681]. At the same time, the Chinese government is committed to investing USD $440 billion in nuclear energy over the next 15 years to build 150 nuclear plants. These efforts will support China's ambitious objective of becoming carbon neutral by 2060. However, they will also enhance the Chinese armed forces by reducing energy vulnerabilities by using less logistically intensive forms of energy in future military operations and improving their nuclear military capabilities (e.g. naval carriers) and beyond (e.g. space systems). China is also tightening its dominance over the Rare Earth Elements (REE) global supply chain [682]. These materials are key to producing new battery technologies and other advanced components, which BLUE is expected to use to support its energy transition. At the same time, China currently has 75% of the world's world's cobalt refining capacity and 59% of its lithium processing capacity [683] which reassures the Chinese dominance over the global battery production [684] and gives them a strategic advantage to develop innovative battery technologies which may unleash disruptive military applications.

Interoperability

The growing reliance on renewable energy sources and battery storage systems requires developing interoperable solutions to integrate them into the power grid. Indeed, renewable energies fluctuate, and their operation is difficult to forecast. Thus, dynamic systems need to be able to communicate the changes in demand to provide a stable supply.

S&T Development

State of Development

This section addresses the state and rate of development of science in this area. Further, it answers the question: What does energy & propulsion mean for the development of related scientific areas or what synergistic relationship does it have with these NATO S&T Priorities:

AI

Artificial Intelligence and Machine Learning will enhance energy management systems. They will support fusion R&D by providing support in managing the high temperatures that need to be generated to spark the reaction.

RAS

Possibly supported by low-power electronics, new technologies in Energy & Propulsion will support long-endurance autonomous systems that can improve Intelligence, Surveillance and Reconnaissance and avoid the need for humans to deploy to hostile and remote regions.

Data

The successful analysis of large data streams coming from different sources will play a key role in ensuring systems operate at maximum efficiency. For example, Big Data Analytics can optimise power generation and plan by matching power supply with the demand for energy from the grid over a short period of time.

Space

Advances in propulsion technology will support deep space exploration and extend the operational life cycle of orbiting satellites. At the same time, innovative space platforms such as in-space solar farms will unharness the sun's full energy potential as a sustainable energy source. Finally, R&D on nuclear energy will support manned operations on the surface of the moon and other celestial bodies.

Hypersonics

Hypersonic flight presents several technical challenges due to the high temperatures generated at such speeds and the extreme conditions in which hypersonic systems operate. Developing Combined cycle engines will offer several technical advantages that will provide momentum to hypersonic technology deployment.

Quantum

Source integration using quantum sensors will allow monitoring of all issues relating to battery performance. At the same time, new vehicle control systems will benefit from precise measurements to improve performance and avoid failure. Quantum computing will also benefit grid optimisation, energy asset optimisation and grid security.

BHET

In the upcoming years' alternative fuels made from plant and plant-derived resources will be increasingly used in the aviation and shipping industries[618]. However, traditional biofuels can be resource-intensive and questionable in terms of energy efficiency [685]. Therefore, biotechnology will be key to moving from conventional bioenergy sources towards advanced bioenergy solutions that leverage organic waste streams, forestry residues, or algae.

E&EM

The increasing demand for battery improvements is forcing the development of advanced manufacturing techniques, such as the use of advanced laser cutting technology, which will provide faster cutting speed and will be able to provide a solution for the higher standards that innovative battery production demands.

STO Activities

Several STO Scientific and Technical Committees have produced significant research on the topic of Energy& Propulsion. At the same time, the Applied Vehicle Technology (AVT) Panel and the Systems Analysis and Studies (SAS) Panel; have various ongoing activities on several topics aligned to these technologies, such as:

- AVT-311 Availability and Quality Issues with Raw Materials for Rocket Propulsion Systems and Potential Consequences for NATO
- AVT-333 Integration of Propulsion, Power, and Thermal Subsystem Models into Air Vehicle Conceptual Design
- AVT-344 Assessment of Micro Technologies for Air and Space Propulsion
- SAS-163 Energy Security in the Era of Hybrid Warfare
- SAS-183 Energy Security Resilience, Capability and Interoperability

Scientometric Analysis

The Science & Technology Ecosystems Analysis Model (STEAM) has analysed over seven million publications, of which 212,000 are aligned to Energy & Propulsion. The chart immediately below (see:J.11) provides a brief overview of the most repeated words within the publications aligned to Energy & Propulsion:

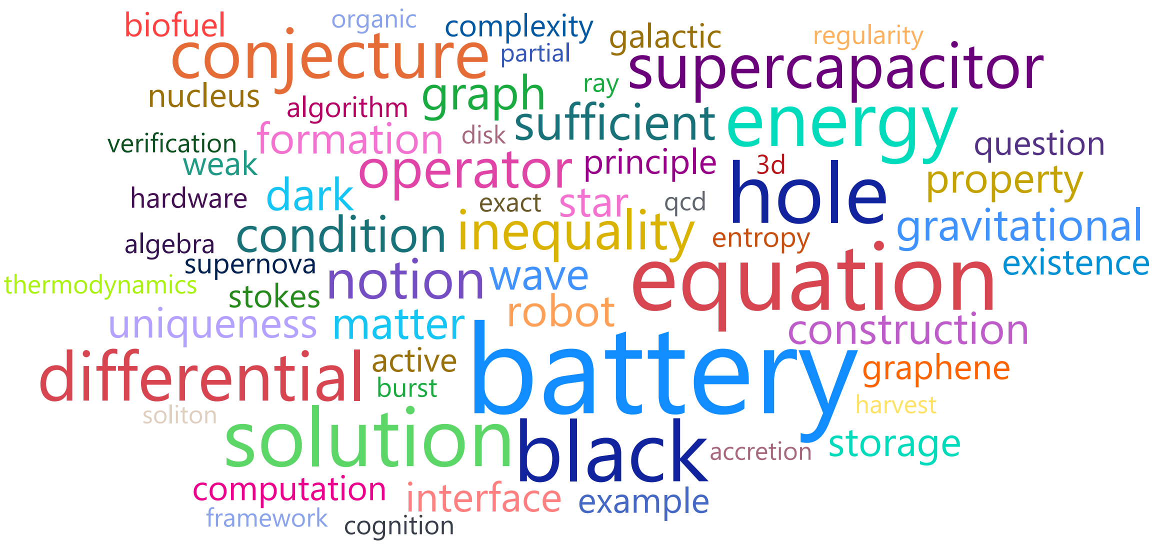


Figure F.9: *STEAM - Energy and Propulsion - Keywords*

Survey Results

The following table presents the assessed potential impact, state, and rate of development and identifies areas for focused research.

Table F.1: *Energy & Propulsion (Energy) 2023 - 2043.*

EDT	Technology Focus Areas	Impact	TRL	Horizon
Energy & Propulsion	Energy Generation	High	5-6	2025-2030
	Energy Storage	High	5-6	2030-2035
	Propulsion	High	5-6	2025-2030
	Transmission	High	5-6	2025-2030

Conjecture Card: Energy and Propulsion

A. Fusion Propulsion

Easier travel amongst the inner planets is made possible through fusion/fission-based propulsion.

B. Green Operations

NATO deployed operations can run 24/7 on green energy.

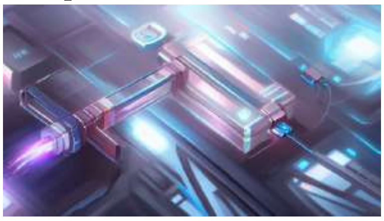
C. Electric Armoured Vehciles

All vehicles up to and including main battle tanks are either fully electrified or hybrid.

D. Self-Charging Batteries

Generate and store renewable energy adequate for an individual soldier's daily needs in portable ways.

E. Superconductors



Quantum materials enable room temperature superconductivity.

F. Capacitors

Battery technology is replaced by rapid super-capacitors, which allow charging of large vehicles in less than 5 minutes.

G. Small Nuclear Reactors

Small nuclear reactors are available and widely used for austere locations and operations.

H. Fusion Arrives

Large-scale fusion reactors become available, providing cheap energy and destabilizing energy markets.

I. Thorium Reactors

Thorium replaces Uranium based reactors, creating abundant and safe energy.

J. Energy Crisis

The price of fossil fuels has tripled since 2022, greatly constraining training and operations.

K. Hydrogen Aircraft

A combination of hydrogen and electric propulsion supports cheap drone and light aircraft operations.

L. Green Biofuels

Greenhouse gas-neutral algae-based and CO2-derived bio-fuels become widely available.

G. Hypersonics

> **Hypersonics**
> "[...] The reality is that the United States has a series of concepts for how it believes it can fight effectively, and we have a good understanding now of where we would employ hypersonic capability in that. It's different than how we believe the Chinese or the Russians look at how they would employ hypersonic capabilities. The Russians, for instance, have used hypersonic capabilities in Ukraine to no noticeable effect. [...]" - *Dr. Kathleen Hicks, Deputy Secretary of Defense (USA)* [686]

Definition

> **Hypersonics**
> *(Advanced) Hypersonic Weapons Systems* (missiles, vehicles, etc.) operate at speeds greater than Mach 5 (6125 kph). In such a regime, the dissociation of air becomes significant, and rising heat loads pose an extreme threat to the vehicle. Hypersonic flight phases occur during re-entry from space into the atmosphere or during propelled/sustained atmospheric flight by rocket, scramjet or combined cycle propulsion. This class of weapon system includes air-launched strike hypersonic cruise missiles (HCM), manoeuvring re-entry glide vehicles (HGV), ground-sea *ship killers*, and post-stealth strike aircraft. Systems of this nature may rely primarily on kinetic effects alone or may include supplemental warheads (nuclear or non-nuclear). Countermeasures against individual or swarms of hypersonic systems are particularly challenging due to their speed and manoeuvrability. [86].

Keywords

Direct Energy Weapons (DEW) · Early Warning Systems (EWS) · Glide Vehicles · Hypersonic · Missile Tracking · Propulsion · Ramjet · Scramjet ·

Developments

Overview

Russia's use of hypersonic weapon systems in the Ukraine invasion has sparked the general public's interest in this type of technology [687, 688]. Nevertheless, the relevance of this technology and the fear of NATO Allies' losing the technological edge were already mentioned in the previous version of this report. Research work in hypersonic flight began as early as 1930 [689], and the experimentation, which began in the late 1950s, included the development of rocket systems that followed a ballistic path (e.g. Project Mercury) and the latter development of "Boost Glide" hypersonic vehicles (e.g. X-15). Since then, Hypersonic R&D has proven highly intensive in time and resources [690, 691], which means that it is only available to some nations with highly developed R&D capabilities. The USA, Russia and China are the current leaders in research and development for military hypersonic vehicle applications [692, 693, 694, 695, 696] with the US alone spending $4.7 billion annually [693] on hypersonic related research (See:G.2). China, in particular, is demonstrating considerable S&T leadership in many aspects of hypersonic flight [697] (see Figure G.1 for one measure of such leadership).

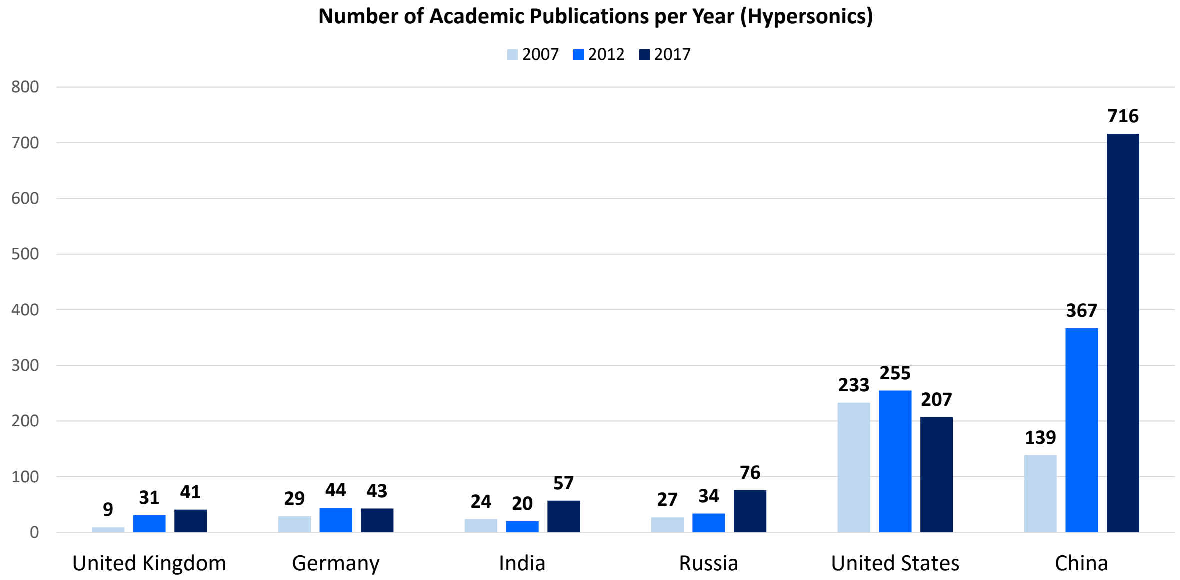


Figure G.1: *Number of Academic Publications (Selected Countries) [698].*

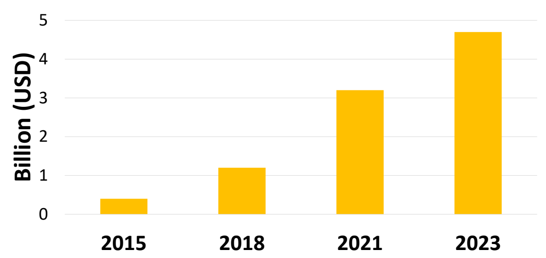


Figure G.2: *2015-2023 US Hypersonic Expenditure Estimates (CREDIT:[699]).*

More importantly, the United States [700], China, and Russia have announced successful tests [701, 702, 703]. In recent years many other nations [73], such as Australia [704], France [705], Japan [706], India [707], and the UK [708] have initiated new hypersonic research programs in combination with other partners (e.g.European Hypersonic Defence Interceptor (HYDEF) project [709]). All of this recent activity in the hypersonic technology field is being considered by some analysts as the beginning of a new arms race [693, 710, 711] (see Figure G.1 for examples on Hypersonic Weapon Systems). By the 2030s, hypersonic missile technologies are expected to expand beyond delivering warheads faster than sound and include hypersonic intelligence and reconnaissance flights [712, 713] and commercial hypersonic airplanes[714, 715]. As noted in [716, 717, 718, 719, 720, 86], the current development of hypersonic systems may be considered revolutionary, in no small measure due a lack of countermeasures and the concern that they lower the bar for the use of military force. Others have noted that while hypersonic weapons are an emerging threat, they are not quite the existential threat suggested by some [721, 722, 723, 724] given the significant technical challenges presented in operating at such high-speeds. For this report, we will divide hypersonic systems development into two categories that are considered to be disruptive in the upcoming years:

Table G.1: *Hypersonic Weapon Systems (CREDIT: [725])*

Country	Programs	Propulsion	Basing Mode
China	DF-17	Boost-glide	Ground-launched
	DF-41	Boost-glide	Ground-launched
	DF-ZF	Boost-glide	Ground-launched
	Xing Kong 2	Cruise	-
Russia	Avangard	Boost-glide	Ground-launched
	3M22 Tsirkon	Cruise	Ship & submarine-launched
	Kinzhal	Cruise	Air-launched
United States	Hypersonic Air-Launched OASuW (HALO)	-	Air-launched
	Long-Range Hypersonic Weapon (LRHW)	Boost-glide	Ground-launched
	AGM-183 Air-Launched Rapid Response Weapon (ARRW)	Boost-glide	Air-launched
	Hypersonic Attack Cruise Missile (HACM)	Cruise	-
	Tactical Boost Glide (TBG)	Boost-glide	Air-launched
	Hypersonic Air-Breathing Weapon Concept (HAWC)	Cruise	Air-launched

Vehicles and Propulsion

Figure G.3: *DARPA HGV Interceptor (CREDIT: [726]).*

A hypersonic vehicle may be an aeroplane, missile or spacecraft. Potential applications include fast, long-range strikes of high-value or high-threat targets, ballistic missile defence, ISR and reusable space transport vehicles. Hypersonic flight occurs during re-entry in the atmosphere from space or during propelled/sustained atmospheric flight by rocket, scramjet or combined cycle propulsion. Advanced *hypersonic* weapons systems (missiles, vehicles, etc.) operate within the atmosphere at speeds higher than Mach 5 (6125 kph) [727] but allow for manoeuvrability [728, 727] and unpredictable flight paths. At such speeds, the dissociation of air (e.g. the breakdown of air molecules into atoms, ions or radicals) becomes significant, and the resulting heat threatens the vehicle. There are four types of hypersonic systems usually discussed:

(1) Boost Glide: Hypersonic glide vehicles (HGV) employ ballistic launch by a rocket but glide and manoeuvre un-powered at hypersonic speeds within the atmosphere. These wave-rider HGVs generally fly at altitudes between 40 to 100 km [729], reaching speeds as high as Mach 25;

(2) Cruise Missiles: Air-breathing hypersonic cruise missiles (HCM) are typically air-launched and powered by scramjets (supersonic combusting ramjets) to maintain hypersonic speeds. Scramjets use thrust produced by compressed air moving at hypersonic speeds, mixed with fuel, and ignited. As a result, they require rockets for assisted take-off or launch in order to accelerate the HCM to Mach 3 or 4, where the scramjet begins to operate. HCMs generally fly at altitudes of 20 - 30 km [729];

(3) Hypersonic Rail Guns: Electromagnetic systems (railguns and coilguns) are expected to achieve hypersonic speeds. These systems use an electromagnetic field to accelerate projectiles. They are foreseen to deliver indirect fire support to engage time-critical targets over longer firing ranges, augment surface-to-air capabilities against very fast-moving aerial targets, and intercept ballistic missiles [730]. One of the benefits of Hypersonic Rail Guns is that their projectiles are more affordable than other systems which rely on chemical energy sources [731]; and,

(4) Hypersonic Aircraft: Encouraging research has been occurring with dual-mode ramjet (DMRJ) systems with Turbine-Based Combined Cycle propulsion, potentially enabling transformational aircraft and UAV capabilities [732].

The development of air-launch sustained cruise hypersonic boost-glide vehicles is progressing, with research focused on affordability, manufacturing, aerodynamic, aero-thermal, and controllability. In particular, future research will need to be focused on:

- **Platforms**: Novel heat resilient materials; new modes of propulsion; miniaturisation, weight reduction; modelling & simulation; new vehicle designs; scramjet propulsion; stealth materials and design; autonomous behaviour (AI and swarms); and, advanced flight control.

- **Materials**: Surface temperatures of HCM/HGV systems can reach over 1000 °C. Developing new mechanically strong and heat-tolerant materials will be necessary [729].

- **Propulsion**: Propulsion systems will need to be expanded and further refined, including increased reliability, efficiency [729, 733] and alternative launch (e.g. EM). Jet engines come in three primary varieties: turbojet, ramjets and scramjets. In particular, while employing relatively few moving parts, scramjets are incredibly complex systems due to various problems with aerothermodynamics, supersonic combustion, fuels, insulation/cooling and structural material and design. Achieving a positive thrust-drag ratio is a significant engineering and technical challenge. These specialised areas include hypersonic flow physics, turbulent transport phenomena, heat transfer, the transition from laminar to turbulent flow, hypersonic inlets, supersonic combustion, advanced functional materials, thermal protection, thermal management stability and control, including control effectors. Research continues to be necessary in the mid-term in order to develop affordable air-launched air-breathing hypersonic weapons capable of sustained high-temperature cruise airspeeds [170]. Sustained hypersonic flight may be achieved by supersonic combustion ramjets (scramjet) but requires acceleration by rocket or other sub-to-supersonic propulsion systems to reach the scramjet's operational regime. Sustained hypersonic flight has been achieved only for a minimal duration ($\sim$ 2.5 min X-51A [734]). Researching new engine designs and operating modes will be critical to developing hypersonic capabilities. In particular, the development of dual-mode engines, which transition from fuel-efficient turbine operation to ramjet mode, will support transformational changes in long-range strike (both HCM and aircraft), ISR, and would enable two-state-to-orbit (TSTO) operations, significantly reducing the cost of space launch [170, 733].

- **Control**: Flight dynamics at hypersonic speeds are complicated by unusual airflow characteristics, necessitating improved modelling and simulation. This, in turn, will help enable research on vehicle control and guidance, which is especially important to improve accuracy, loss of control and autonomous behaviour.

Counter-Hypersonic Systems

The recent deployment of operational hypersonic weapon systems [702] and their potential disruptive effect on conventional assets [735] has increased the need for the development of countermeasures to maintain strategic stability [736]. Use of interceptors (e.g. Glide Breaker [162, 737]), electronic countermeasures, lasers and other directed energy systems (DEW) (e.g. high power radio frequency weapons), or more advanced tracking satellite systems [738] offer some options for countering hypersonic threats. However, opposing hypersonic systems is complex and remains a priority. More specifically:

- **Sensors & Tracking**: Countering HCM & HGV will require improved terrestrial and space-based sensors for detection, identification and tracking, as well as improved navigation and control to ensure successful intercepts. Integrated data fusion and autonomous functions will need to be improved to support the short decision times available.

- **Hard Kill**: Development of new anti-hypersonic missiles or hyper-velocity projectiles suitable for the counter-hypersonic role will present a major technological challenge. Directed energy weapons (DEW) may also provide a hard-kill capability, but the very nature of hypersonic vehicles will make this a challenge.

- **Soft Kill**: Using cyber, EW, DEW and decoys to counter hypersonic weapon systems.

Military Implications

Figure G.4: ZIRCON HCM Test (CREDIT: [702]).

Military application is possible both for propelled (e.g. Aircraft or HCM) and un-propelled hypersonic (e.g. HGV) flight vehicles [690]. Powered hypersonic vehicles can be used for reconnaissance purposes [713, 712, 739] such as a successor to the SR-71 [740] or for fast or long-range strike with hypersonic cruise missiles [703]. Such high speeds allow for a rapid strike against time-critical targets from safe standoff distances [687], keeping the launch platform well outside contested areas. Advanced Anti-Access/Area Denial capabilities have pushed out the boundaries of contested areas. Hypersonic flight counters this trend and allows greater standoff operations for the first strike. Also, the extreme speed of hypersonic penetrating systems makes kinetic interception very difficult.

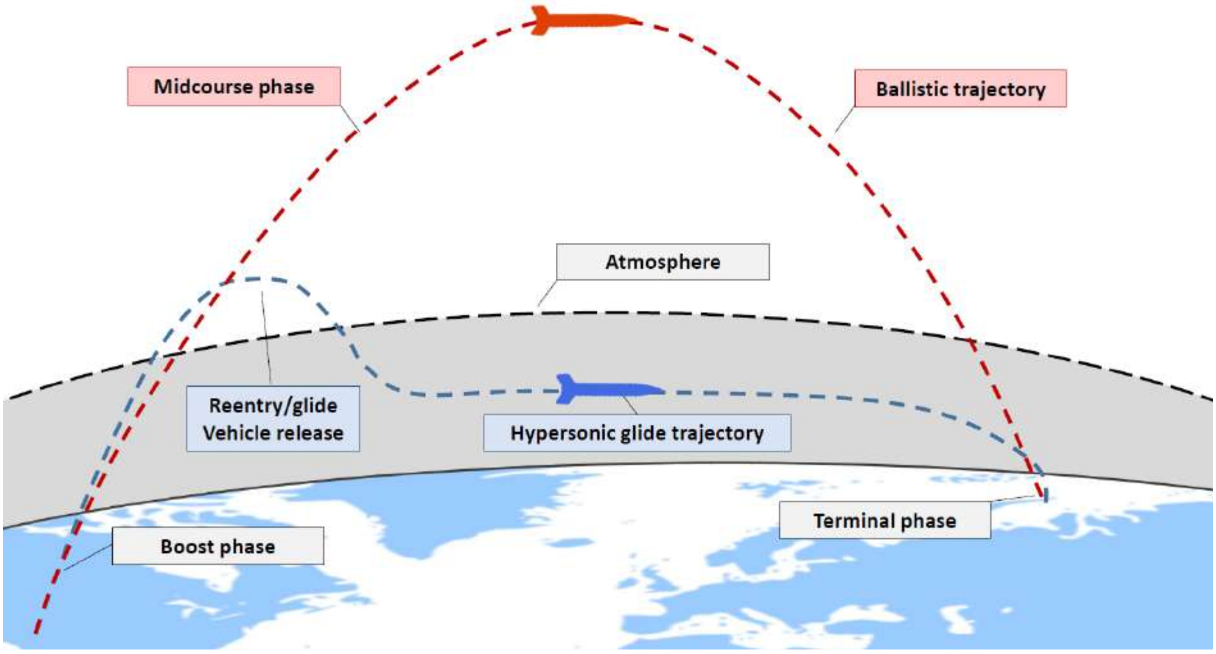


Figure G.5: *Flight Trajectories of Hypersonic Boost-Glide Missiles and Ballistic Missiles (CREDIT: [741].)*

Even if hypersonic systems have proven capable of military application, some analysts claim they are not a major disruptor [742, 743], even as an advancement over established cruise and ballistic missile technologies [744]. Whatever the case, the truth is that these systems are gaining momentum, and their development is becoming a top priority for militaries across the globe [691]. BLUE and RED are both engaged in developing this kind of system. BLUE is looking at this system as an enhanced capability for quick, precision response below the ICBM/nuclear level [73]. However, RED is developing systems that could be armed with nuclear warheads [73, 691]. The “warhead ambiguity” of hypersonic weapon systems could lead up to escalation [745]. For now, these systems will likely be more strategic than tactical, and for high-value or high-threat targets only because of the high system cost [746]. Nevertheless, the possibility of reducing investment in traditional systems and diverting it towards hypersonic weapon systems [735] may increase their number and availability.

BLUE

Over the 20-year horizon of this report, hypersonic weapon systems will remain the province of peer or near-peer competitors due to significant technical challenges and high capability costs. Increased strike capabilities, more effective defensive countermeasures [747], and hypersonic aircraft will challenge Alliance operations. In particular, the possibility of a non-nuclear (kinetic) decapitation strike against strategic and operational high-value targets (e.g. critical bases, capital ships [748] etc.) will significantly compress strategic and operational decision times in a manner that is potentially profoundly destabilising [86]. In particular, BLUE will benefit from Hypersonic Technology in the following areas:

Engage

Hypersonic weapon systems' high speed and ability to manoeuvre could become a decisive military advantage when striking adversary high-value targets from a safe standoff distance [687]. Using hypersonic systems will allow rapid, highly challenging-to-engage and precise high-energy (kinetic) strikes. In swarm or salvo, this would enable increased kinetic kill probability of high-value targets.

- **Propelled hypersonic vehicles (e.g. HCM)**: These systems will fly at high altitudes with speeds around Mach 6 – 8 and limited manoeuvre capability. This presents significant countermeasure and intercept challenges. HCMs, in particular, would provide a significant capability for penetrating RED air defences due to their high speed of operation, manoeuvrability and operating altitudes between the engagement space of traditional air and ballistic missile defence systems [729]. Such capabilities are also valuable for engaging high-value time-sensitive targets or for rapid re-targeting during flight.

- **Un-propelled hypersonic vehicles (e.g. HGV)**: These systems may be used by BLUE as warheads on a ballistic missile having the advantage of manoeuvring capability for targeting precision and defence penetration. These vehicles will reach higher hypersonic speeds (> Mach 10) but for a shorter duration. Thermal problems can be addressed by heat protection/insulation.

Protect

BLUE is currently developing defensive systems [73] [749] in order to minimise the utility of RED systems and maintain its strategic deterrence [750]. Hypersonic systems are challenging to defend against by their very nature (speed and manoeuvrability). At the same time, the high altitude range in which these systems operate (20 km to 60 km) creates a gap between traditional missile defences [751]. Currently, BLUE is engaged in the development of the following:

- **Defensive Countermeasures**: Hypersonic Glide Vehicles or Hypersonic Cruise Missiles could also be utilised for offensive counter-air operations. At the same time, BLUE is exploring several options, which include interceptor missiles, hyper-velocity projectiles [752, 753], laser guns, and electronic attack systems.

- **Tracking Systems**: Currently, most terrestrial-based radar systems have limitations in detecting hypersonic weapon systems [73]. For this purpose, BLUE is developing new space-based tracking systems [73] and other innovative solutions [754] able to track and ultimately intercept RED hypersonic weapon systems.

Sustain

- **Aircraft**: Hypersonic aircraft will sustain Alliance capabilities in a post-stealth operational environment, providing a technological edge in a *post-stealth* world [720]. Such systems may enable the rapid deployment of special forces or materials around the world in a matter of a few hours.

Inform

- **ISR**: Propelled hypersonic vehicles will be used for high-altitude rapid ISR collection (e.g. as a successor to the SR-71) as an alternative to collection by satellites or HALE UAVs. Long-range Intelligence, Surveillance, and Reconnaissance is another potential application. While manned systems are possible, long-range ISR by a hypersonic UAV would be more flexible than reconnaissance satellites with a possible option for weapon delivery.

RED

Figure G.6: *Kh-47M2 Kinzhal (Dagger): 2018 Moscow Victory Day Parade (CREDIT: kremlin.ru).*

RED has demonstrated advanced HGV, and HCM programs [73]. Russia has allegedly used Kinzhal hypersonic missiles (Figure G.6) at least three times during their brutal and unprovoked war of aggression against Ukraine [755]. Also, in July 2022, during Russia's Navy Day, it was announced by Putin that the Russian navy would soon receive Zircon Hypersonic Cruise Missiles (see Figure G.4) [756]. The latter was preceded by an announcement concerning the Zmeevik ballistic missile [757]. This 'new' system may revitalise a 'cold war' R&D program on 'new' anti-ship ballistic missiles [703] and resembles the Chinese DF-21D, and DF-26 anti-ship ballistic missiles [758]. On its side, China has successfully tested two HGVs. The first one is the DF-ZF (previously known as WU-14 an unpowered HGV designed to be launched from a ballistic missile such as the DF-17 or the DF-41 [697] and then 'glide' to its objective at hypersonic speed. The other is named Xingkong-2, or Starry Sky-2 [697], which after being launched, is sustained by powered flight [759]. Both DF-ZF and the Xingkong-2 are advertised as nuclear-capable hypersonic missile delivery vehicles designed to penetrate BLUE's ballistic missile defences [73]. At the same time, China is also testing Hypersonic Unmanned Aerial Vehicles for ISR purposes [739]. Finally, in September 2021, North Korea tested Hwasong-8, a ballistic missile with a hypersonic glide vehicle.

Figure G.7: *DF-17 on Communist Party 70th Anniversary (CREDIT:[760]).*

RED is looking at hypersonic technology with potential nuclear implications, increasing their already destabilising nature. At the same time, non-nuclear Hypersonic Weapon Systems already seriously threaten BLUE. Indeed, the kinetic impact of a hypersonic missile would suffice to compromise BLUE vessels severely [750], which would find themselves extremely vulnerable to such attacks due to the current lack of countermeasures. On the other hand, some Subject Matter Experts claim that RED hypersonic systems are overhyped and are just an evolution of traditional ballistic missiles [689, 744, 715]. Overall, as described in this appendix, RED hypersonic systems will significantly affect deterrence posture [761], military planning, and the overall BLUE policy/doctrinal background for operations over the next 20 years.

Interoperability

The latest developments in hypersonic systems build upon a number of development cycles spread out over the last 60 years. However, the latest R&D cycle has brought with it the possibility of operational use, as noted in [728]:

> *"Hypersonic weapons use electronic capacity, sensor quality, and miniaturisation to create a new threat ... They're fast and manoeuvrable. That combination creates a threat ... There are flight tests from Russia, China, and other countries that show accelerated progress."*

Given the high cost associated with hypersonic R&D, interoperability issues are expected to be small, as these systems will remain firmly under national control. Hypersonic defence systems may present some interoperability challenges, but these are expected to be consistent with the deployment of conventional systems. More critical will be the (offensive & defensive) capability disparity within the Alliance, along with C2 issues associated with integrated tactical warning and threat assessment.

S&T Development

State of Development

This section addresses the state and rate of development of science in this area. Further, it answers the question: What does Hypersonics mean for the development of related scientific areas, or what synergistic relationship does it have with these NATO S&T Priorities:

Space

Countering HCM & HGV will require improved terrestrial and space-based sensors for detection, identification and tracking, as well as enhanced navigation and control to ensure successful intercepts. In addition, integrated data fusion and autonomous functions will need to be improved to support the short decision times available.

Quantum

Countering HCM & HGV will require improved terrestrial and space-based sensors for detection, identification and tracking, as well as enhanced navigation and control to ensure successful intercepts. In addition, integrated data fusion and autonomous functions will need to be improved to support the short decision times available.

Materials

Surface temperatures of HCM/HGV systems can reach over 1000 °C. Therefore, developing new mechanically strong and heat-tolerant materials will be necessary [729].

Energy

Sustained hypersonic flight may be achieved by supersonic combustion ramjets (scramjet) but requires acceleration by rocket or other sub-to-supersonic propulsion systems to reach the scramjet's operational regime. Sustained hypersonic flight has been achieved only for a minimal duration ($\sim$ 2.5 min X-51A [734]). The associated research on new engine designs and operating modes will be critical to the broader development of hypersonic capabilities. In particular, the development of dual-mode engines, which transition from fuel-efficient turbine operation to ramjet mode, will support transformational changes in long-range strike (both HCM and aircraft), ISR, and would enable two-state-to-orbit (TSTO) operations, significantly reducing the cost of space launch [170, 733].

E&EM

Cyber, EW, DEW and decoys are used to counter hypersonic weapon systems.

STO Activities

Several STO Scientific and Technical Committees have produced significant research on hypersonics. It is worth mentioning that the Applied Vehicle and Technology (AVT) Panel has conducted several activities (e.g. AVT-136/190/195/199/200/205/206/208/234/240) on hypersonics. In addition, in August 2020, AVT delivered 'AVT-ST-008', a comprehensive report on the status and challenges of Hypersonic Operational Threats (HOT). Currently, the STO has numerous ongoing activities on several topics aligned to hypersonics, such as:

- AVT-346: Predicting Hypersonic Boundary-Layer Transition on Complex Geometries
- AVT-352: Measurement, Modelling and Prediction of Hypersonic Turbulence
- AVT-359: Impact of Hypersonic Operational Threats on Military Operations and Technical High-Level Requirements
- AVT-SCI-379: Technologies Needs for Hypersonic Operational Threats (TecNHOT)
- AVT-SET-396: Technological challenges for hypersonic flights
- AVT-ST-009: Technical Support to NATO Next Generation Rotorcraft Capability (NGRC)
- SAS-159: How could Technology Development Transform the Future Operational Environment
- SAS-166: War-gaming Multi-Domain Operations in an A2/AD Environment
- SET-296: Radar against Hypersonic Threats

Scientometric Analysis

The Science & Technology Ecosystems Analysis Model (STEAM) has analysed over seven million publications, of which almost 10,000 are aligned to Hypersonic technologies. The chart immediately below (see:J.11) provides a brief overview of the most repeated words within the publications aligned to Hypersonics:

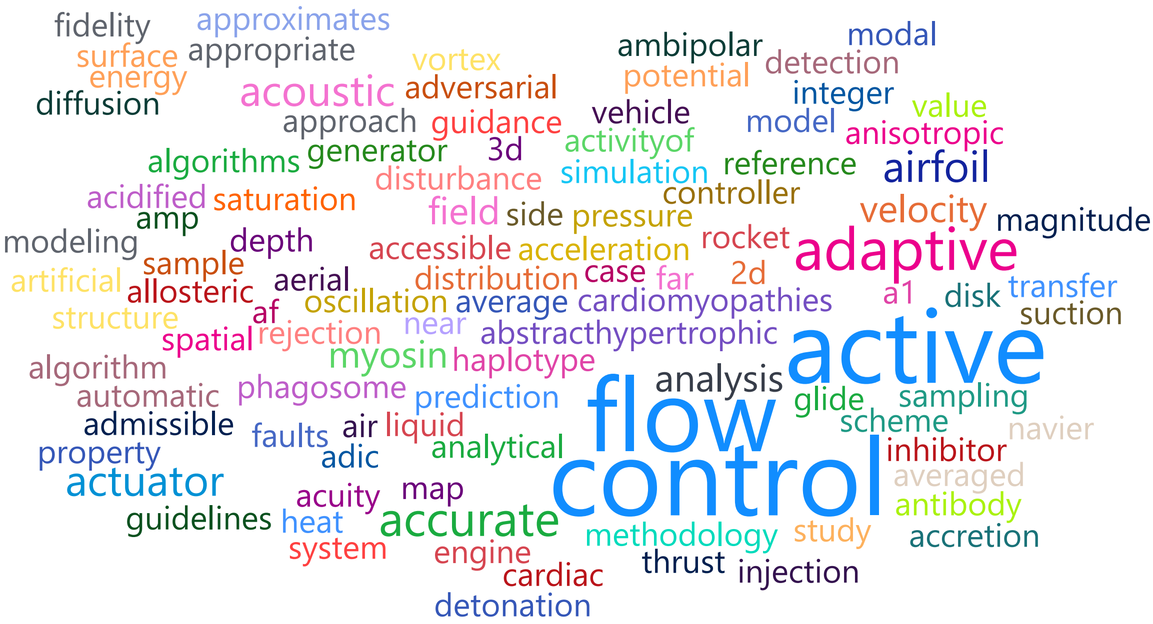


Figure G.8: STEAM - Hypersonics - Keywords

Survey Results

The following table presents the assessed potential impact, state and rate of development and identifies areas for focused research.

Table G.2: *Hypersonics 2023 - 2043.*

EDT	Technology Focus Areas	Impact	TRL	Horizon
Hypersonics	Counter Hypersonics	High	3-4	2030-2035
	Vehicles & Propulsion	High	5-6	2030-2035

Conjecture Card: Hypersonic Technologies

A. Energy Beam Self Defense

Automatically defend air, maritime and land assets from incoming hypersonic missiles or enemy systems using high-powered energy beam weapons (e.g. lasers).

B. Hypersonic Missile

Launch a precision hypersonic attack from ground, surface, air or orbit capable of absolute destruction of a large building, aircraft carrier, air terminal or complex.

C. Super Destructive Projectiles

Propel hypersonic projectiles over great distances without needing chemical propellant, delivering destructive power through kinetic effect.

D. Underwater Launch

Launch hypersonic weapons (glide or cruise) while submerged for strike or ISR missions.

E. Very Fast Air

Employ manned aircraft, UAVs and missile systems supporting hypersonic cruise, increasing responsiveness, situational awareness and survivability.

F. Hypersonic Swarms

Precision control of swarms of hypersonic vehicles or missiles in flight targeting air, land or naval forces.

G. Propulsion and Materials

Exploit next-generation materials, propulsion and manufacturing to reduce hypersonic systems' cost and availability greatly.

H.Defensive Shield

Simultaneously identify and destroy multiple incoming ballistic or hypersonic missiles inside or outside the atmosphere.

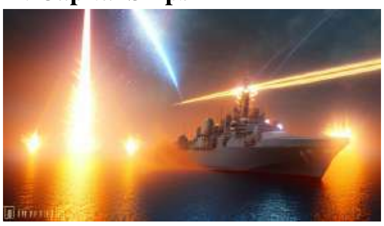
I. EM Countermeasures

Disable targeted electronic systems on hypersonic vehicles, even those with electromagnetic shielding or countermeasures.

J. Decapitation Strike

Greatly reduced warning time of a limited nuclear "decapitation" strike.

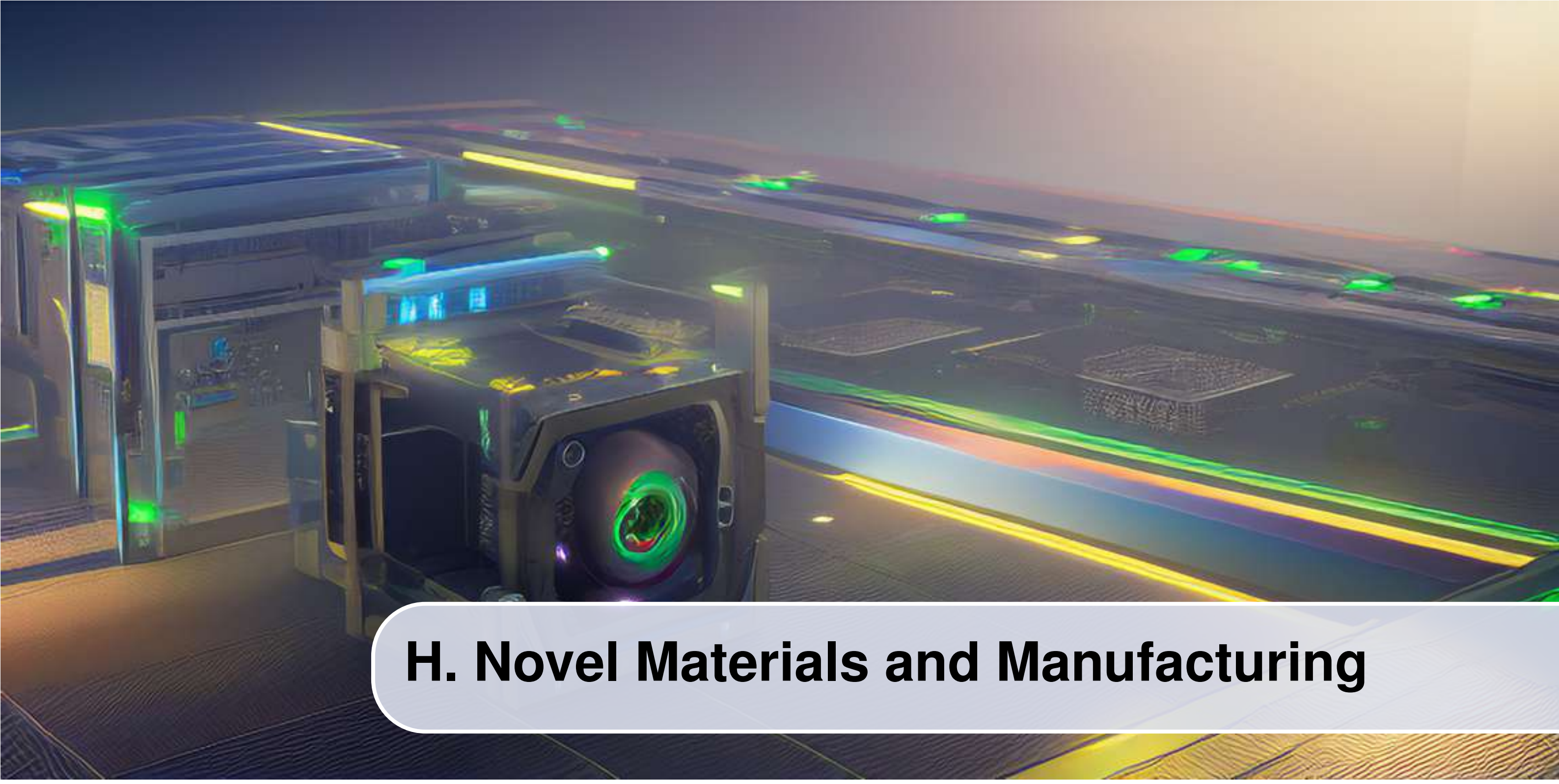
K. Capital Ships



Cheap, plentiful and accurate hypersonic systems render capital ships non-employable within a thousand km of a conflict zone.

L. Effective Missile Defence

New counter-hypersonic systems (kinetic and non-kinetic) greatly improve strategic ballistic missile defence destabilising the nuclear balance.



H. Novel Materials and Manufacturing

Novel Materials and Advanced Manufacturing

"Advances in materials and manufacturing will have a profound effect on Defence and national security over the coming decades. The use of novel materials with additive and hybrid manufacturing will make for more efficient, lower waste products, highly customised design and production, and embedded electronics and sensors, enabling the collaborative, rapid design and manufacture of spare parts for weapons, combat vehicles, and other equipment." - *A. Zelinsky* [762]

Definition

Novel Materials and (Advanced) Manufacturing (or *Materials*)

Advanced (novel) materials are artificial materials with unique and novel properties. Advanced materials may be manufactured using techniques such as those drawn from nanotechnology or synthetic biology. Development may include coatings with extreme heat resistance, high-strength body or platform armour, stealth coatings, energy harvesting & storage, superconductivity, advanced sensors & decontamination, and bulk production of food, fuel and building materials. Research into graphene, graphyne, other novel 2-D materials, and topological materials is an area of high potential and growing interest. *Additive Manufacturing*, which is often used as a synonym for *3-D printing* [763], is the process of creating an almost arbitrary 3D solid object from a digital model through layered addition of materials. Additive Manufacturing can be used for: rapid prototyping; in situ production & repair of deployed military equipment; and production of precision, custom or unique parts.

Keywords

Novel Materials · Additive Manufacturing · Agile Manufacturing · Bio-materials · Graphene · 2D Materials · Black Silicon · Flexible Displays · Nanotechnologies · Smart Coatings · Bio-fabrication · Bio-manufacturing

Overview

Overview

Humanity's advancement as a species is often measured by reference to the dominant materials employed at the time. From neolithic stone tools, through the weapons of the bronze age, to the mastery of iron, steel and aluminium, the advance of civilisation has relied on advances in material science. Moreover, current research and development in the material sciences form the basis for disruptive advances in industry and manufacturing. Such research focuses on designing, developing, assembling, and optimising new and advanced materials and the manufacturing techniques necessary to produce new technologies and electronics. This area has been spurred by advances in *Data*, advanced analytics, AI/ML, Space, Quantum, Hypersonics and Biotechnologies.

Research benefits in this area include rapid adaptation to changing requirements, on-demand printing, greater efficiency in manufacturing, design and development, platform survivability, new materials or designs unachievable through casting or reductive methods, and nano-to-micron-scale assembly. At the same time, such research is responding to SWaP-C challenges and opportunities generated by other EDTs. Among these challenges are the need for greener technologies, industrial processes, and reduced energy usage.

Novel materials and advanced manufacturing (Materials) research underlie much of the success of the industrial revolution. Moreover, developments in novel materials and manufacturing are expected to demonstrate disruptive and emergent aspects over the next 20 years [762, 764, 765, 766]. While elements of this EDT, such as agile manufacturing (e.g. 3D/4D printing), are assessed to be highly disruptive in areas of capability development, acquisition and logistics, the underlying technologies are already well in place and continue to be developed, expanded and used at a brisk pace by industry. However, at the cutting edge of research are the development and exploitation of new materials (e.g. graphene first discovered in 2004 and other 2-D materials such as graphyne [767, 768, 769]); design of quantum nanomaterials [770, 771, 772, 773, 774]; creation of new material properties [775]; production of hitherto *impossible* designs; new manufacturing methods (e.g. biotechnology-based [245]); nanoscale manipulation of materials; mixed materials printing; and, the use of AI and BDAA to find new materials with novel properties. These research areas are driven by a desire to discover or exploit new and unique physical properties (e.g. superconductivity), provide environmentally friendly options and address SWaP-C challenges (e.g. energy).

Advances in this area of research can be categorised into two broad groups:

- Novel Materials; and
- Advanced Manufacturing.

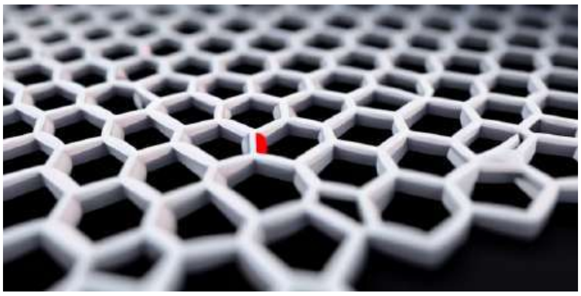
Novel Materials

Research into novel materials and advanced manufacturing is a vast field of study [776, 762], touching on the truly unique and surprising properties of 2-D materials, new 3-D fabrication methods, unique designs, smart materials, quantum M&S, nanotechnologies, and bio-manufacturing. These have a wide range of applications, with the generation and storage of energy (e.g. batteries) being one of the most disruptive.

Materials research underlies much of the advancement of modern technology from electronics to clothes (e.g. nylon). Nevertheless, materials' properties and behaviours often constrain these technologies. As a result, breakthroughs in the material sciences can generate considerable impact across the technological landscape [119, 121]. Interesting areas include new 2D materials (beyond graphene) such as graphyne (an allotrope of carbon), novel polymers, nanomaterials and meta-materials. A few of the most interesting and potentially disruptive will be considered in this section.

A revolution in 2-D materials research [777, 778, 779, 776] has emerged since the isolation and initial characterisation of graphene and more recently, the families of topological insulators and transition metal dichalcogenides. These and other novel materials have generated considerable R&D excitement, kick-started by the discovery of graphene in 2004 and the awarding of the 2010 Nobel prize in Physics to its discoverers Geim and Novoselov [780].

Graphene is a carbon-based material with a wide range of extreme mechanical, physical, chemical and electrical properties not found in any other known material. It is chemically stable, non-toxic, lightweight and relatively easy to produce from widely available raw materials. Graphene's individual properties exceed those of conventional materials, and its combination of these properties is unique. Graphene is one of the thinnest, strongest, stiffest, and more stretchable crystal materials [781]. As a result, 2D materials are an area of intense research, and development [119, 121], focused on exploring the unique properties of graphene and similar 2-D materials, such as another form of carbon called graphyne [769, 782, 783].



2-D materials hold considerable promise for truly disruptive effects. They are widely expected to lead to significantly improved materials for applications in aerospace (composite structures), high-frequency electronics (terahertz, radar, cooling), functional coatings (anti-icing, corrosion protection), energy storage (batteries, ultracapacitors), camouflage (radar absorbers), weapon technologies (energetics, missiles), protection (armour, textiles), sensors (photodetectors, pressure/strain, chemical) and portable devices (displays). Other novel 2-D materials such as phosphorene [784], hexagonal boron nitride [785], and transition metal dichalcogenides [780] have also shown unique and surprising characteristics.

Because of these unique properties, there is intense interest in identifying alternative 2-D materials. Recently eight new materials have been identified that have a structure similar to graphene [119]: antimonene [786, 787, 788], arsenene (a single-layer buckled honeycomb structure of arsenic) [789, 790], bismuthine [791], borophane [792, 793], borophene [794], phagraphene [795], phosphorene[784] and stanene [796, 797, 798]. Other similar 2-D materials such as Cr2ge2te6 [799], Rhenim Disulfide [800], Titanium Carbides [801] and Molybdenum ditelluride [802] have unique optical, ferromagnetic, physical or electrical properties. The search is also for materials with unique electronic, optical and physical properties, with applications in electronics and energy storage drives. This includes exploring entropy-stabilised oxides [803, 804]. These unique properties are especially useful for potential defence and security applications.

2-D materials R&D is taking place around the world. China, in particular, has taken a leading role in 2-D material research [805] and is making significant progress towards commercialisation, as is South Korea. In January 2013, graphene was identified as one of the two European Union Future and Emerging Technology Flagship projects with a budget of 1B€ over ten years, forming Europe's most significant research initiative ever [806].

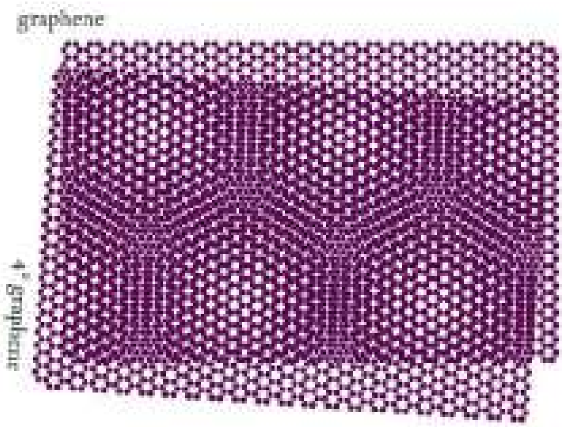


Figure H.1: *Moire of Twisted Bilayer Graphene (CREDIT: WikiCommons)*

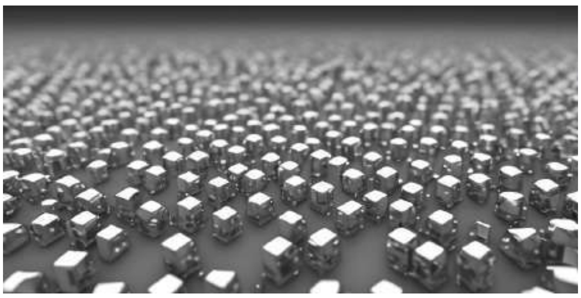
The fundamental properties of these 2D materials may be critical enablers for future technologies. While challenges remain in terms of manufacture and scalability, graphene and other 2-D materials will offer game-changing technological improvements, eventually. However, over the next 10-15 years, military capability development and application will most likely be evolutionary. Advances will probably be found by combining 2D materials to form new classes of layered heterostructure materials, as well as with the use of traditional bulk materials. Early experiments around stacked two-layer, three-layer graphene sheets (rotating the layers by a small twist angle (Figure H.1)) [807] have also demonstrated remarkable electrical properties (e.g. superconductivity) [808, 809] and yielded promising biosensors [810].

Generally, improved robustness, operational life and reduced weight/size can be expected. This research will lead to novel enhanced devices and uses, such as:

- Integration with conventional semiconductor devices to improve infra-red photo-detection for thermal imaging or to achieve faster optical modulation for broadband communications;
- Biological and chemical warfare detectors;
- Barriers to specific biochemical molecules;
- Conductive membranes for flexible or printed electronics [811];
- High-speed electronics to support the development of imaging and ranging (radar) as well as Terahertz (THz) communication frequencies [811];
- Cooling of electronics leveraging the superior thermal conductivity of graphene [811]; and
- Development of graphene optoelectronics and photonics for solar cells, touch screens, photodetectors, and ultrafast lasers [812, 813].

Current 2D materials research is extremely broad, ranging from energy generation and storage through optoelectronics and bio-chemical sensing to flexible, lightweight, yet mechanically strong fabrics and conducting polymers. From a defence perspective, the focus may be directed toward those technologies that can provide key advantages in the near to medium term; one of these key areas is optoelectronics. Industry is testing applying graphene to various technologies relevant to electronics, medicine, aerospace, automotive, energy storage, water desalination, composites, coatings and paints, solar technologies, oil and communications.

Other materials are also being explored for application to defence problems. For example, although well-studied and widely applied, silicon has additional properties or states of interest. An example is black silicon, micro-structured silicon, which absorbs visible and infrared light strongly due to surface micro-spike traps [814]. It has potential applicability in producing photodetectors, night-vision systems and solar cells. Another type of material being explored is topological materials [775, 815], a class of quantum materials whose quantum states are unnaturally stable under environmental changes. Topological insulators [816] is particularly interesting due to an unusual combination of insulating and conducting properties.



Polymers are integral and essential to modern economies and militaries, [817] and have been intensely studied for over a century. Nevertheless, several notable research areas exist [818], for example, creating complex topological structures, functional polymer materials, sustainable materials, biopolymers and self-healing polymers.

Nanomaterials are materials with nanoscale (one-billionth of a meter) features that may exhibit unique optical, electronic, biological or mechanical properties. Two critical reearch areas are [773, 819, 772, 790]: **bionanomaterials** and **quantum dots**.

Metamaterials are another area of intense research and development [820, 821, 578], originally developed in the early 2000s. Metamaterials are functional engineered materials that employ distinctive physical structures or patterns to enable optical, acoustic and broad electromagnetic material properties that are not naturally found. This allows unparalleled control to direct and manipulate waves, be they electromagnetic or acoustic. Research areas of special interest are acoustic, electromagnetic and dynamic metamaterials.

In addition, to post-silicon semiconductor developments, new materials are being developed to support the demands of increased data storage and processing requirements. For example, phase-change materials (PCM), as a data storage medium, are being used to develop analogue memory for storage and computation in neuromorphic devices [822, 823]. Furthermore, Van der Waals (vdW) materials such as Gadolinium tritelluride (GdTe3) [824, 825] show promise as a medium for data storage.

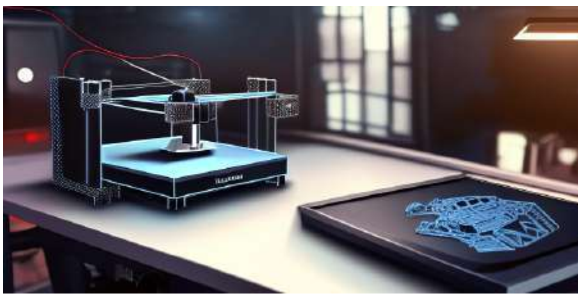
As already noted, a considerable range of research is being conducted to develop new materials, not all of which fall neatly into the categories defined above. Some more exciting developments are occurring in superconductors, materials for harsh environmental conditions, ultra-lightweight composites, nanoscale, and eco-friendly materials.

Advanced Manufacturing

Advanced manufacturing methods cover many techniques more attuned to sustained advances in well-defined innovation processes. However, it would be misleading to see developments in this EDT as simply part of the normal refinement of industrial processes. Several technologies are being developed that are emerging as significant disruptors. Two are of particular note for their potentially disruptive effects on NATO: **3D/4D Printing** and **biomanufacturing**.

3D printing and the additive manufacturing process it supports entered the mainstream of manufacturing and public consciousness in early 2000. While the terms are often used interchangeably, 3D-print adds materials in an iterative approach to build up objects from digital models. At the same time, additive manufacturing uses 3D printing at an industrial scale to manufacture products [826]. Over the last few years, significant research advances have been made [827] in printing methods, devices, materials development, printing process and post-process modifications [828]. Novel applications and new ways continue to develop rapidly and are areas of intense research. One promising application area is based on biomimetics, e.g. replicating biological structures through 3D printing [829].

The increased use of 3D printing can potentially be highly disruptive in a defence context. For example, equipment and vehicle production lines are often closed after production ceases. This loss of capacity means all spare parts must be produced before closing the line. Consequently, military equipment is often retired and made surplus once the ability to find spares ceases to be cost-effective. 3D printing theoretically can recreate new parts as long as the digital models are available, extending the life of major pieces of equipment. Similarly, production lines could be re-established quickly and effectively.

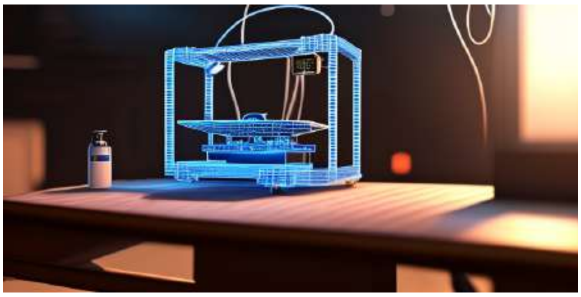


First developed in 2013, 3D printed materials that transform under changing environmental stimuli such as pressure, heat, pH, light, humidity, or temperature are called 4D printed materials [119, 830, 831]. Such materials hold promise for new designs or sensors, especially in biomedical applications such as biomedical robots, tissue engineering or bio-scaffolds. [832, 833, 834].

One of the 3D-printing's biggest potential applications is biomedical, where living tissue (bone, skin, organs, etc.) is printed using 3D printers, and the printing of customised and designer drug tablets on demand, bespoke medical appliances or biological scaffolding [835]. Such technologies can revolutionise medical treatments, and combat casualty care, especially in forward medical units and for rehabilitation [119].

While additive manufacturing methods such as 3D/4D printing continue to develop, new ways of nano and micro-assembly are being explored, looking to synthesise, assemble and construct materials from the atomic to the macro product scale, seeing potential application in energetics, optics, and therapeutics, electronics [836, 837, 838] and other micro-nano printing applications. Printing and assembly of nano-micro scale materials, so-called nanofabrication [839], is being used for a variety of purposes, including the development of small-scale ultra-thin optics, miniaturised batteries and electronics, quantum dot synthesis, DNA origami-directed assembly, nano sub-assemblies of larger objects and nanoscale structures [840].

On a larger scale, 3D-printed extruded concrete provides great design flexibility and structural options for large buildings, especially those with complex geometries [119, 841, 842]. This may significantly reduce construction costs, increase deployment options for buildings in operational areas, and potentially reduce the costs for garrison locales. This technology is particularly disruptive in emergency shelters or extra-terrestrial habitation using locally sourced materials, allowing reduced costs and viable habitats for human habitation on the moon or other such bodies [843, 844]. 3D printing of nano-ceramics [845] is also being explored and is a very challenging process.



The means of 3D printing vary widely and are highly material-dependent. Depositional methods using polymers are well-established and widely used. However, two new approaches and applications are being explored: robocasting and wire arc additive printing. Robocasting employs a moveable nozzle that extrudes a thin filament of paste material [119]. Applications are especially rich in wearables, soft robotics and medicine [846]. Wire arc additive printing uses wire source materials, which are then melted and deposited in layers in a manner already well-developed for plastics. The advantage of such a method is that it lowers the cost and time for fabricating complex homogenous or mixed metal parts, a valuable property to support repair and maintenance facilities in operational theatres.

Additive manufacturing (AM), or 3D printing as it is also known, creates three-dimensional solid objects of virtually unlimited shape from digital models and a wide variety of metals, plastics and resins [847]. AM is achieved using an additive material process, whereby successive layers of material are laid down in different forms. AM is distinct from traditional material removal or machining techniques, which rely on cutting, milling or drilling (subtractive processes). AM is already heavily influencing commercial production and supply chains. Some caveats for AM application are component size, precision and surface quality limitations and the potential need for post-fabrication machining. The resulting manufactured materials may have unique properties and be impractical or impossible to produce using conventional manufacturing methods. AM technologies may be used for, among other things, rapid prototyping, in-site production and repair of deployed military equipment, and precision, custom and unique parts production. Industry is leading the development of 3D printing, with the global 3D printing market rising from 5.8 billion USD in 2016 to 55.8 billion USD by 2027 [848].

Over the last 20 years, AM techniques, equipment and technology have been developing at a rapid pace [849, 850, 851], where they have become a key component of high-value manufacturing and agile manufacturing. AM (or 3D printing) is a broad term encompassing seven core technologies [763]: • VAT photo-polymerisation • Material jetting • Binder jetting • Material extrusion • Powder bed fusion • Sheet lamination • Directed energy deposition.

Current AM techniques mostly apply for limited production runs, specialised designs, or prototyping [852]. However, AM systems (limited as they are) are growing popular in the home and industrial markets. As such, they are becoming widely available and have moved well beyond printing simple 3-D plastic models (e.g. Figure H.2). Roughly two-thirds of US manufacturers have adopted 3D printing, with around

50 per cent already using it for prototyping and final products. Nevertheless, AM systems are not yet at the level of maturity necessary to replace traditional machining and manufacturing methods for widespread, full-sized industrial production. However, this is changing, and the availability of 3D printing capabilities enables agile manufacturing and edge production in various industries.

Potential 3D printing applications are seen to be: • Concept modelling and prototyping. • Low-volume complex parts, such as rocket engines • Replacement (obsolescent) parts • Structures using lightweight, high-strength materials • Mixed-materials and embedding additively manufactured electronics directly in/on parts • Repair parts on the battlefield, on-board ship or in space • Large structures directly in location, thus circumventing transport vehicle size limitations • Manufacture of novel designs or use of unique materials • Large structures [854] such as buildings (using local materials) or weapon systems (such a ship [855]) • Bio-materials such as replacement tissues, organs and body parts.

Figure H.2: *SpaceX Super Draco Printed Thrust Chamber [853] (CREDIT: SpaceX)*

The related process of 4D printing [856] merges 3D printing with advanced materials sensitive to environmental conditions. These materials are programmed to change their form or physical behaviour when subject to an environmental trigger (e.g. heat, pressure, current, light, etc.).

A related technology, nanotechnologies, are those processes for manipulating materials at the atomic scale, often leading to novel material characteristics. For example, the Ministry of Defence in the UK predicts that medical nanobots and nano-enhanced C4ISR devices (e.g. micro-radar for miniature UxVs) will begin to be used from 2030 on-wards [857].

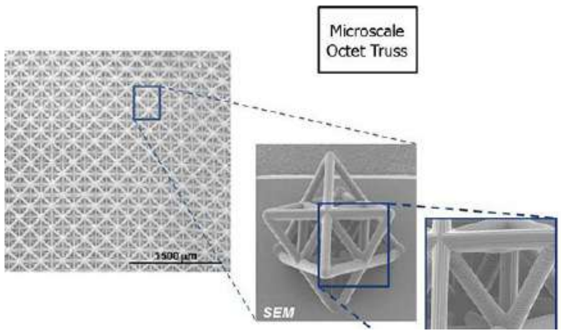


Figure H.3: *3D Micromaterials [858] (CREDIT: DARPA)*

Current AM (3D/4D) and nanotechnologies directly affect defence and security [859]. However, these technologies are also widely available and *dual-use in nature* [852], thus providing near-peer and non-state actors with similar advantages. This also supports a massive increase in RED's ability to leverage system designs obtained illicitly or provide embargoed parts such as those needed for advanced aircraft or missiles [860].

The development of increasingly sophisticated techniques and tools to sequence, synthesise and manipulate genetic material has led to the rapidly maturing discipline of synthetic biology. These developments, in turn, have opened up new approaches to materials R&D, nanoscale manufacturing, bio-fabrication and bio-manufacturing. These approaches utilise engineered biological agents (cells, proteins, fungi, etc.) to assemble or build various products, ranging from pharmaceuticals, organs, tissues, leather, and even concrete [861]. Specialised bio-robots or *xenobots* for nanoscale manufacturing are also at the early stage of development [241].

A completely different approach to manufacturing leverages biological processes with wide application [862, 863, 864, 865, 866]. Such biomanufacturing or bio-fabrication leverages the growing success of new biotechnologies for industrial-level production and manufacturing. While such methods go back millennia to the invention of beer and wine, direct manipulation and engineering of biological systems have opened new approaches and opportunities. This area of research allows for unique fabrication and manufacturing capabilities for the large-scale production of materials, chemicals and pharmaceuticals. Simplistically, biological systems are engineered to produce a product [867] by creating new biological constructs (genes, cells or organisms) or modifying existing biological entities. Biomanufacturing methods hold great promise in energy reduction, increased innovation, reduced raw material needs, and sustainability [868, 862], but may also present unknown health and safety risks. Areas of particular note are the use of biomanufacturing for construction (bio-cementation and bio-remediation), electronics (thin, flexible substrates), consumer products (thereby reducing wastes), food manufacturing and pharmaceuticals. An application of particular interest is using microbial capabilities for bio-production in space [868], e.g. the B-SURE program in DARPA.

Military Implications

BLUE

Many defence applications exist for advanced materials, nanotechnologies and 3D/4D manufacturing. Following historical developments, it can be assumed that future systems will be lighter weight, stronger and more power-efficient due to the incorporation of advanced materials. In particular, Materials will impact operational and enterprise capabilities.

Enable

Improved product development via shortened design cycles and increased cost/time-effective development will support the development of new military capabilities and response to changing geostrategic needs.

AM can support design optimisation unlimited by conventional machining constraints, leading to reduced costs, weight, longevity, and improved performance. Such cost reductions and increased effectiveness of new designs and high-cost items, especially in the aerospace or maritime environments, would also support a more adaptive and agile force structure. For example, single-crystal turbine blades coated with thermal barrier coatings or ultra-quiet submarine propellers involve intricate designs and complex material processing. They are, therefore, costly. The effective repair of such components using AM will significantly reduce the cost of ownership and increase operational availability.

AM may also be used to develop speciality materials having special chemical or physical properties, including drugs, nutritional supplements, and other substances requiring nanoscale manufacturing assembly processes.

Prepare

AM will support the development of task-tailored capabilities through specialised mixed materials printing (e.g. print-to-order UxVs).

Project

Developing novel fabrics, building materials and large-scale 3D printing of buildings will allow for improved strategic deployment and rapid development of necessary operational infrastructure.

Sustain

New lighter, stronger, more resilient materials and onsite 3D printing capabilities will reduce equipment burden, which is particularly important for long-range operations and critical for aircraft systems.

Developments will improve maintenance and logistics by reducing stocks of spare parts (at home, on ships or abroad), increasing parts availability and reducing shipping expenses. Spare parts could be manufactured on demand locally, replacing hardware storage with storage of printable designs. Such parts could be produced onsite based on a 3D scan of the component, thereby significantly extending operational life, reducing the logistic tail and minimising life-cycle costs. This also includes creating commodity-like materials, with increased efficiencies enabling economies of scale, e.g. fuel, food, and building materials. Further, the printing of on-demand medical capabilities will improve combat casualty care.

Nano-engineered materials may greatly improve water and wastewater treatment. In addition, this will reduce the logistics burden, especially during crisis response operations.

Engage

Developments will allow new antennae to be designed, improving the detection of (weak) signals (RF/microwave or optical) and extending the physical range of operating platforms (either for communications, range-finding or thermal imaging/heat-seeking). In addition, task-tailored autonomous weapon systems on-demand and onsite [869] will improve engagement effectiveness and provide operational flexibility. Reduced signatures due to new materials and coatings will also support the more effective engagement of targets.

Protect

Developments will yield membranes and materials that identify and protect against bio-chemical attack or provide higher sensitivity to detection (as well as selectivity) of explosive vapours. Further, lightweight, high-impact resistant materials for new armour and soldier systems, substantially lighter than current technologies, will improve equipment and individual protection against various threats.

New materials will enable improved stealth and camouflage. Smart coatings increase vehicle survivability by reducing the reflection and radiation of electromagnetic waves.

For example, graphene has been shown to improve ceramics' fracture toughness, which is expected to translate into enhanced ballistic protection if applied to ceramics used for armour. In addition, graphene may enhance ballistic fibres' strength and elastic properties, such as ultrahigh molecular weight polyethene. Graphene is also expected to be useful as a coating on military uniforms to improve weather resistance and condition monitoring using smart/intelligent textiles. Chemical protection of gloves, masks, etc., may also be improved. Finally, radar reflections from all platforms (land, sea and air) will be accomplished by adding graphene to polymers for radar-absorbing coatings.

Inform

Integral lightweight, flexible electronics woven into fabrics will support covert wearable devices. New materials and manufacturing will also support the fielding of novel sensors with unique capabilities for sensing environmental (e.g. CBRN) and other phenomena not currently detectable or at scales needed across the battlespace.

C3

Beyond silicon materials, including graphene, will support cheaper, faster, more resilient electronics for communications (wider bandwidths) and improved computation. More specifically, developing new materials will help increase miniaturisation and energy efficiency, improving computational performance.

RED

The benefits for RED forces are similar to those available for BLUE. More specifically for AM:

- Civil/commercial interests mainly drive development. Therefore, these technologies will be available to a wide range of countries, non-state actors and military forces. As such, the novel use by asymmetric threats (firearms, IEDs, task-tailored weapons, etc.) must be anticipated and may pose a considerable threat to BLUE.

- There are serious concerns about managing AM technologies for defence applications. For example, digital designs are required for AM, which are easily reproduced (e.g. via 3D scanning), shared, hacked, modified, counterfeited and stolen.

- The broad availability of AM and associated novel designs will encourage the proliferation of defence technology to non-state players, non-friendly states, and counterfeiting of components. In addition, embargoed parts could also be readily produced (e.g. F-14 parts [870]), limiting the effectiveness of sanctions.

Interoperability

No specific interoperability challenges are foreseen with the development or use of 2D materials. Nevertheless, this may lead to some technical disparities amongst NATO forces.

Development of AM as an integral NATO capability will require design, software, IP, cyber, certification and manufacturing standards to be developed if advanced 3D/4D printed parts are used in advanced weapon systems. Safety requirements alone suggest that if we are to exploit AM parts in high-stress areas such as aerospace routinely, we must address their certification and qualification as original or replacement parts. This requirement will require an extensive understanding of all factors leading to variability in properties and methods to inspect, characterise, and certify components accurately. In addition, using digital designs, scanning and 3D printing of parts may violate contractors' IP or increase the risk of legal action against Alliance forces while limiting operational agility and reducing operational availability.

S&T Development

State of Development

This section addresses the state and rate of development of science enabled by advances in Novel Materials and Advanced Manufacturing. It answers the question: What does Materials research mean for developing related scientific areas, or what synergistic relationship does it have with these NATO S&T Priorities? It is not an exhaustive list but rather indicative of the cross-fertilisation and synergistic developments across EDTs that may yield truly disruptive capabilities.

Data

- **Computational Power**: New post-silicon semiconductor materials will increase the computational power to process sensor data and exploit complex big data analysis.
- **Data Storage**: Increased data storage and access speed improving data retention and utility.
- **Enhanced Sensing**: Lower data collection, processing and exploitation costs.
- New materials and manufacturing methods hold the promise of faster and more energy-efficient computation, as well as improved data collection.

AI

- **Computational Power**: New post-silicon semiconductor materials will increase the computational power to run complex AI algorithms and reduce energy use.
- **Data Storage**: Increased data storage and access speed will greatly enable the processing of training data necessary for AI/ML systems.
- **Enhanced Sensing**: Lower costs and energy-efficient sensors will support the collection of training and situational data feed into AI/ML systems.

RAS

- **Rapid Manufacturing**: 3D printing and other advanced manufacturing methods will allow for rapid and agile onsite production of task-tailored autonomous systems. Further, new large-scale printing methods may support the rapid creation of larger crewless vehicles, greatly reducing costs and improving operational effectiveness through increased numbers of highly effective systems.
- **SWaP-C**: Mixed materials printing and new lighter-weight materials will support lighter, durable, stronger and more adaptable UxVs. This, in turn, will reduce costs and vehicle propulsion requirements.
- **Sensors**: Novel manufacturing techniques (e.g. mixed materials 3D printing) will all integration of sensors directly into the
- **Efficiency and Effectiveness**: Lighter and more durable materials and new stealth/camouflage materials will provide more energy-efficient and operationally effective capabilities.

Space

- **Effectiveness and Efficiency**: Lightweight, stronger and durable materials will enable the development of new launch capabilities, satellites and sensor systems, increasing the effectiveness and durability while reducing costs and improving operational effectiveness. Improvements to thermal, radiation and vacuum resilience will help reduce wear and increase resilience and, ultimately, longevity.

- **Customisation**: 3D printing and new materials will support the development of new satellite/propulsion designs, integrated sensors and novel structures. Further, deploying such manufacturing methods into the space domain itself, while potentially using *"local"* materials, will greatly reduce the costs of space systems while supporting increased on-orbit repair.

- **Human Activity**: On-orbit 3D printing will enhance manned operations in space, including medical care through bio-printing and 3D-printed habitation.

Hypersonics

- **Effectiveness and Efficiency**: Lightweight, stronger, heat resistant and durable materials will enable the development of hypersonic weapons and manned systems capable of operating in the hypersonic regime. This, in turn, will reduce the costs of hypersonic systems.

- **Novel Design**: 3D printing and new materials will support the development of novel body, control and propulsion designs. Further, this will greatly reduce costs and increase hypersonic systems' availability.

Energy

- **Energy Efficiency**: New 2D-enabled materials and 3D printing technologies will improve battery efficiency, performance and safety. At the same time, improvements in materials and superconductivity may improve energy transmission, distribution and usage. In addition, using new materials (such as aerogels and other insulators) will increase energy efficiency and heat loss.

- **Integration and Design**: Developments in 3D printing may allow for the integration of batteries into structures and vehicles. 3D printing, in contrast to traditional manufacturing methods, will reduce the cost of producing solar and wind systems and potentially support novel designs.

- **Nanotechnologies and Metamaterials**: Developments will allow designer materials with tailored properties for specific energy use cases. For example, novel coatings may reduce hull drag and increase the corrosion resistance of ship hulls, and nanoparticles may improve combustion or green energy collection.

E&EM

- **Computational Power**: New post-silicon semiconductor materials will enable improved performance, reliability, efficiency and miniaturisation of semiconductors.

- **Nanotechnologies and Metamaterials**: Developments will enable the development of new technologies for manipulating the EM spectrum or electrical/magnetic fields, including novel antenna designs, stealth materials and camouflage.

- **Novel Design**: Advanced manufacturing methods will allow 3D integration of chips and chiplets, increasing performance and power reduction.

BHET

- **Bioprinting**: 3D printing of biological scaffolds and supporting agents will support the generation of organs, tissues and other biological structures. Supporting materials such as hydrogels, ceramics, metal alloys, and biodegradable polymers will allow the selection of materials with tailored properties for the designed biological functions.

- **Pharmacuticals**: Nanotechnologies will enable targeted drug delivery with increased efficiency, effectiveness and reduced side effects.
- **Biosensors**: Nanomaterials and metamaterials will enable more resilient, cheaper, sensitive and tolerated biosensors.

STO Activities

Several STO Scientific and Technical Committees have produced significant research on Materials technologies. Many panels have ongoing activities on several topics aligned with these technologies. The following is a sample of ongoing activities:

- AVT-TW-017: Advanced Materials in Mechanical Systems for Extreme Operating Environments
- AVT-364: Environmental Regulation on Energetic Systems and its Impact on Critical Munitions Materials and Capability
- AVT-371: Materials and technologies for electro-optical camouflage (Cross-Panel)
- AVT-311: Availability and Quality Issues with Raw Materials for Rocket Propulsion Systems and Potential Consequences for NATO
- AVT-343: Novel Materials to Mitigate Rare Earth (RE) Criticality in High-Speed Motors
- AVT-384: Novel Materials and Manufacturing in Military Vehicle Design
- AVT-ET-226: Characterisation of thermal protection materials designed for extreme environments
- HFM-ET-206: Biomanufacturing of National Security Materials
- AVT-TCMSM: Mechanical Systems Structures and Materials Technical Committee
- HFM-ET-204: Additive Manufacturing to Support Forward Deployed Medical Forces- Printable On-Demand Medical Capabilities
- AVT-342: Interoperability of Additive Manufacturing in NATO operations
- AVT-372: Military value of graphene technologies
- SET-289: Nanotechnology for Optics & Infrared Photo Detection

Scientometric Analysis

Keywords associated with Novel Materials and Advanced Manufacturing derived from STEAM analysis are shown in Figure H.4.

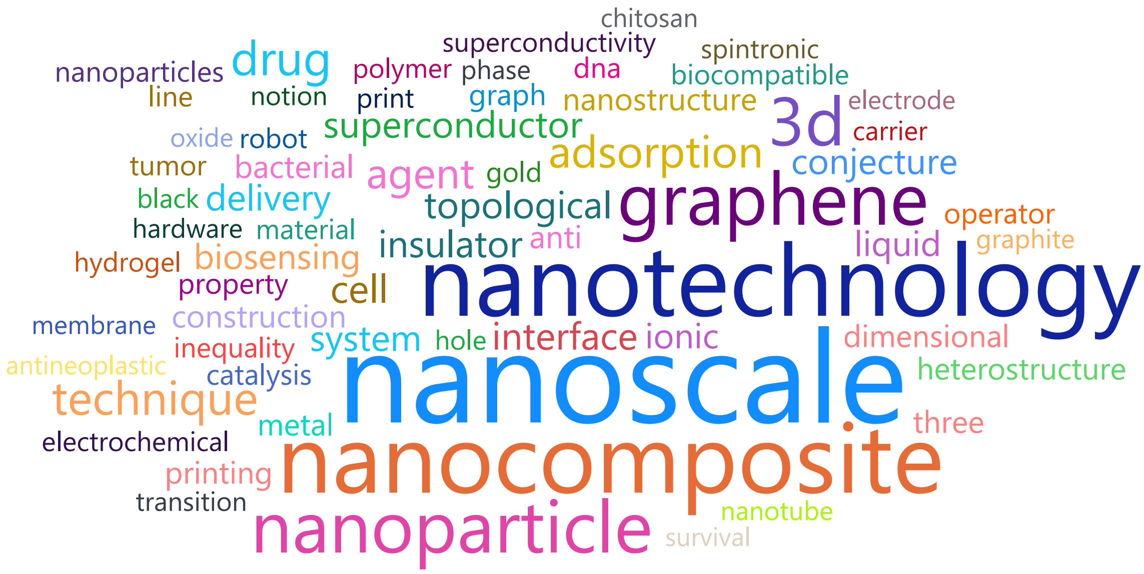


Figure H.4: *STEAM - Materials - Keywords*

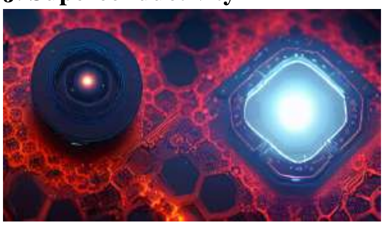
Survey Results

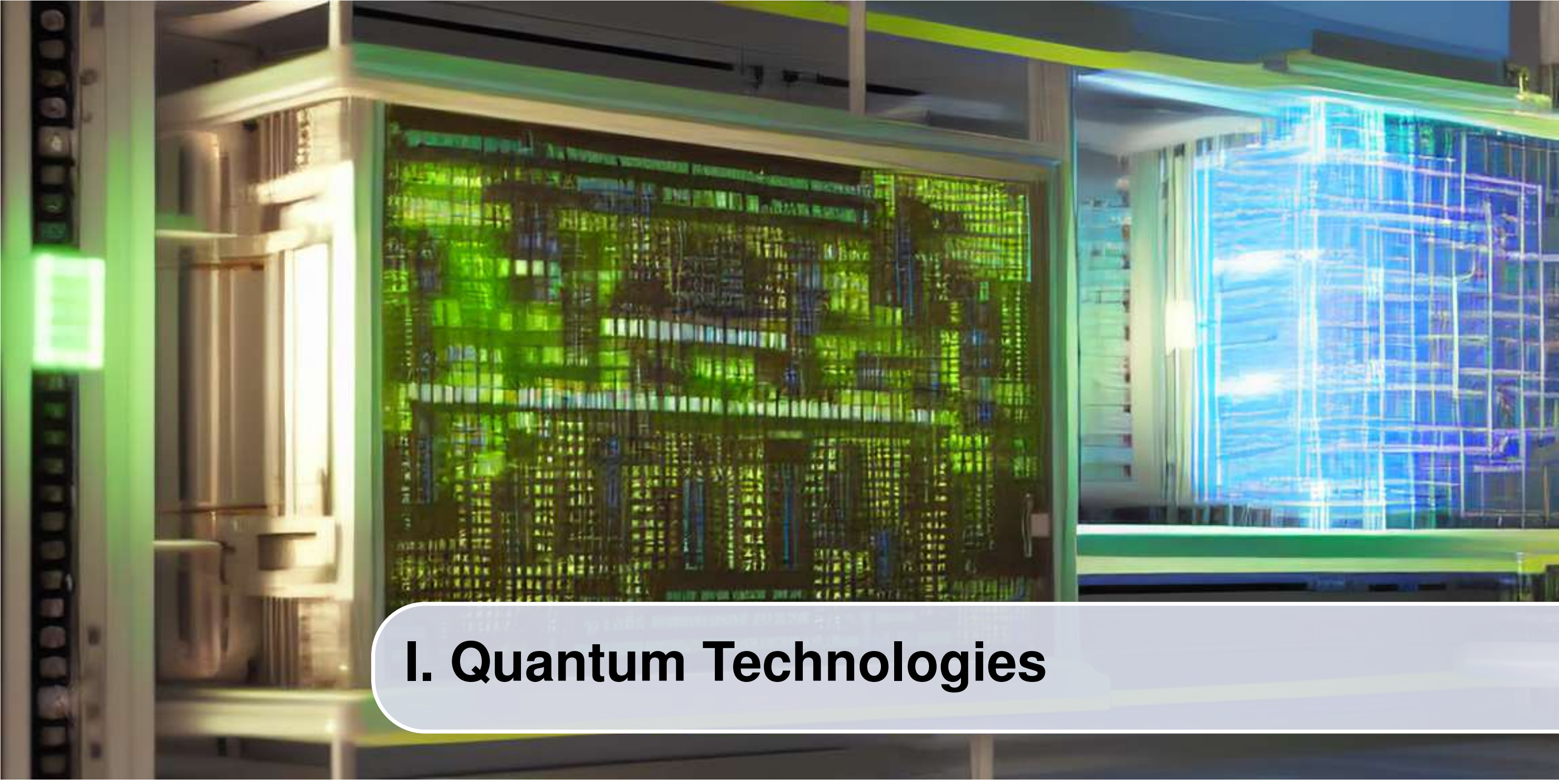
The following table presents the assessed potential impact, state and rate of development and identifies areas for focused research.

Table H.1: *Novel Materials and Advanced Manufacturing (Materials) 2023 - 2043.*

EDT	Technology Focus Areas	Impact	TRL	Horizon
Materials	Nano-materials & Nano-manufacturing	High	5-6	2025-2030
	Novel Design & Additive Manufacturing	High	5-6	2025-2030
	Novel Materials	High	3-4	2030-2035

Conjecture Card: Materials and Advanced Manufacturing

A. Nanoengineering  Nano-engineered materials greatly improve water and wastewater treatment during crisis response operations.	**B. Smartlite Armour**  Wear lightweight body amour or extremely flexible clothes but resistant to bullets or directed energy fire.	**C. Enhanced Repair**  Self-healing materials, additive manufacturing and bio-manufacturing, allow equipment to be maintained or recycled indefinitely.
D. Platform Printing  Rapidly develop and deploy task-tailored land vehicles, naval vessels, aircraft, habitation and spacecraft.	**E. Graphene**  Graphene composite armour corrosion-resistant and order of magnitude lighter than 20th-century systems.	**F. Temporary Shelters**  Build large stable shelters from extremely resilient, extremely lightweight material that self-packs in minutes.
G. Novel Propeller Design  Design and 3D print hither-to-impossible ultra-stealthy submarine propellers.	**H. Textured Explosives**  3D print embedded and hidden energetic materials in structures and systems (available to state, non-state actors, and individuals).	**I. Spider climbing**  Climb walls or windows with sticky material applied to hands, knees, or feet.
J. Superconductivity  Twisted 2D materials support room-temperature superconductivity.	**K. Microscale Printing**  3D printing of micron-scale meta-materials (Micro AM), including tendons, ligaments and acoustic metamaterials.	**L. Geopolitical**  Advanced manufacturing methods reverses the globalization of the supply chain, thus disrupting the geopolitical environment.



I. Quantum Technologies

Quantum Technologies

“We’re moving very fast. We’re trying to stay on the road, not able to see clearly what’s coming our way, but that being said, there is a glimpse of a few things on the horizon ... The emergence of quantum technology is a little like moving from a digital world in black and white to a quantum world in color.” - *David Awschalom, University of Chicago* [871]

Definition

Quantum Technologies (QT)

Next-generation *quantum technologies* exploit quantum physics and associated phenomena at the atomic and sub-atomic scale, particularly quantum entanglement and superposition. These effects support significant technological advancements primarily in cryptography; computation; precision navigation and timing; sensing and imaging; communications; and materials.

Keywords

Quantum · *Superposition* · *PNT* · *Entanglement* · *Photonics* · *Post Quantum Cryptography* · *Quantum Sensors* · *Quantum Imaging* · *Quantum Materials* · *Simulation* ·

Developments

Overview

Quantum mechanics has its origins during the beginning of the last century and is generally used to describe the behaviour of matter at the atomic scale (less than 10 nm). Quantum phenomena underlie modern technology, including the transistor, nuclear energy, electron microscopes, superconductivity, photoelectric detectors, and various types of medical imaging, such as functional magnetic resonance imaging and positron emission tomography. Lasers and solid-state devices also exploit the rules of quantum behaviour.

Modern military systems rely on classical, statistical, quantum, and relativistic physics. The first quantum revolution, in particular, provided the foundation for many of today’s military technologies, including transistors, computer chips, lasers, and modern communications. These practical applications have transformed society and the battlefield, but recent advancements have led to even greater opportunities. Over the last forty years [872], a new generation of quantum technologies has slowly emerged, capable of producing, exploiting, and engineering more subtle aspects of quantum phenomena. As a result, previously unimaginable technological advancements are now possible.

The second quantum revolution, as it is sometimes called [873, 874], is expected to have a profound and revolutionary impact [875]. These second-generation quantum-enabled technologies are currently the subject of intense research, and development [876, 877, 878]. While the practical application of these effects is currently being investigated and employed, there is increasing recognition that they may play a pivotal role in a larger technological revolution that includes autonomy, advanced manufacturing, material science, energy storage, and next-generation quantum effects [879]. However, developing these second-generation technologies also presents significant challenges, which must be addressed before their full potential can be realised.

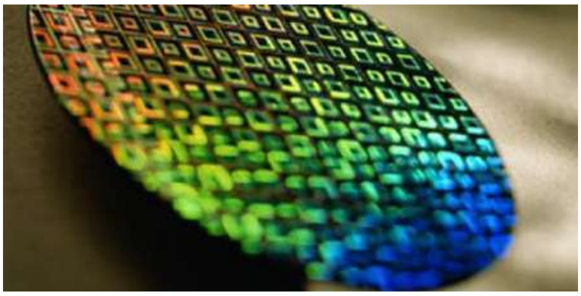


Figure I.1: A Semiconductor Wafer [CREDIT: WikiCommons]

The second quantum revolution, often dated back to the 1980s but with no clear starting point, involves the engineering, manipulation, and control of individual quantum states [872]. These second-generation quantum-enabled technologies rely on quantum phenomena such as superposition and entanglement and offer the potential for revolutionary military and security capabilities [357, 880, 881, 882, 877, 883, 876]. Currently, massive investments and research efforts are being aimed at developing these quantum technologies, with proposed applications in ultra-sensitive sensors, positioning, navigation, and timing (PNT), communications, and information science. This research has led to the development of next-generation technologies, such as uber-sensitive magnetic and gravimetric sensors, incredibly accurate clocks, unbreakable encryption and communications, and quantum computing that can solve certain classes of problems more efficiently than classical computing [884, 875, 885, 886, 887, 888]. However, developing these technologies poses significant challenges, and much work must be done before they can be fully realised.

Quantum technologies are generally broken into three broad overlapping areas [876, 889]:

- **Quantum computing**: The use of superposition and entanglement to create qubits capable of being used for computation. The term quantum information science may also be used, although this includes not only quantum computers but the development of new specialised quantum-based algorithms, programming languages, interfaces, etc. Quantum computers are best seen as employing specialised processors suitable for a very limited (but important) class of problems in optimisation and simulation [890].

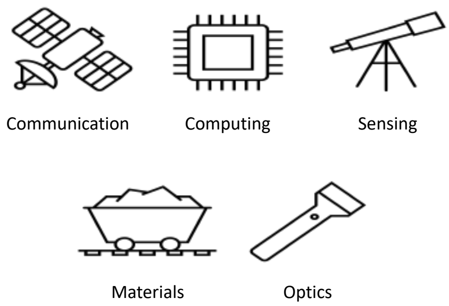
- **Quantum communication**: The use of secure or cryptographic methods for communication using quantum properties (e.g. entanglement) to provide intrusion detection or improved cryptographic techniques. Quantum key distribution (QKD) is a well-known example of this technology. Post-quantum cryptography is a separate area using enhanced encryption algorithms that are not amenable to solutions by quantum computers. The quantum internet may also be considered part of this research area, defined as a (theoretical) network built through entangled quantum communication networks and computers.

- **Quantum sensing**: Using a quantum system, quantum properties, or phenomena to measure a physical quantity. The term quantum metrology is often used to distinguish sensors used for in situ measurements through quantum effects, especially in the context of measurement of fundamental physical constants. For example, measuring magnetic or gravitational fields for positioning, navigation, and timing (PNT) is an example of militarily relevant quantum sensing. It is, therefore, often suggested as a separate technological area.

Two other areas of research may be identified, and both act as technological enablers for the three areas identified above:

- **Quantum materials**: These are materials whose properties are only explainable with reference to quantum phenomena. For example, 2-D materials such as graphene or graphyne are often called quantum materials, as are quantum topological materials whose electronic structures are different (and significantly more complex) than those shown by metals or insulators.

- **Quantum optics**: The application of quantum mechanics to understand and exploit the interaction of light with matter. This covers various applications such as interferometry, photonics, quantum computing, communication, sensing etc.



In considering this EDT, we will restrict consideration to the three generally accepted areas of militarily relevant quantum technologies. That is not to downplay development in these areas, but to recognise they are often considered fundamental aspects of other EDTs.

Large investments continue to be made around the globe in quantum technologies and are expected to reach nearly 30 billion USD in 2022. Unfortunately, the hype around such investments and developments continues to be equally large, often confusing near-term technologies such as quantum sensing with long-term and high-risk technologies such as quantum computing. While this hype has only grown over the last two years, there are indications that the reality of the long and difficult technical challenges involved is dampening enthusiasm in some areas. As a result, some authors and commentators have lamented the hype around quantum computing [891, 892, 893, 894]. Others have referred to the excitement around quantum technologies as a highlighting a *"fascinating social phenomenon"* and an example of a *"classic bubble"* [895].

Developments for quantum *computing* are primarily driven by commercial interests, while those in quantum *sensing, communications* and *PNT* are motivated by defence and security interests. National levels of investment are substantial and increasing [896], but the focus remains predominantly on commercial applications. Collaboration across nations will be instrumental in advancing basic science, particularly defence applications. As per [884], in the longer-term for QT, typically over 20 years from now, a step-change in quantum capabilities is expected when quantum devices can reliably exploit entanglement despite noise across a variety of time and distance scales and when the number of entangled logical qubits per device increases.

Quantum technologies will not come upon us together en masse, but sensors, communications and computers will arrive in a staggered fashion as their technology evolves. If successful, these technologies will profoundly affect military operations [877, 883, 876].

Although new quantum technologies have the potential for a revolutionary impact on NATO operations, most (but not all) are in the early stages of development, and significant technical challenges lie ahead before operational systems are developed. Using ultra-sensitive gravimetric, magnetic or acoustic sensors will significantly increase the effectiveness of underwater warfare capabilities, potentially rendering the oceans transparent [897]. Quantum radar [898, 899, 899] might make stealth technologies obsolete, provide more accurate target identification, and allow covert detection and surveillance. Accurate clocks will enable the development of (precision) positioning, navigation and timing (PNT) systems for use in GPS-denied or inaccessible areas (e.g. under ice). Unbreakable quantum key encryption will support more robust and secure communication. Quantum computing, potentially the most disruptive quantum technology of all, can render previously untenable classical computational tasks in areas such as optimisation, BDAA, AI, and modelling & simulation viable. This computational edge can significantly increase the decision-making and operational effectiveness of NATO forces and render current encryption techniques and encrypted data *crack-able*.

Interoperability considerations will be critical for the successful implementation of some quantum-enabled capabilities. Standardisation around quantum encryption and communications protocols will be a more immediate concern. PNT, sensors and computing will present fewer interoperability challenges as these will be tightly integrated into operational capabilities, which may also lead to significant disparities in operational performance between alliance members.

Of all the emerging digital technologies (EDTs), quantum technologies are the most nascent and variable in their development. In particular, the operational viability of new sensors demonstrated at the laboratory level is a significant area of ongoing research [900]. This development is widely acknowledged to be at a much lower level of technical readiness than other quantum technologies [901, 902]. Precise positioning and timing (PNT) and quantum key distribution (QKD) are much closer to being fielded operationally.

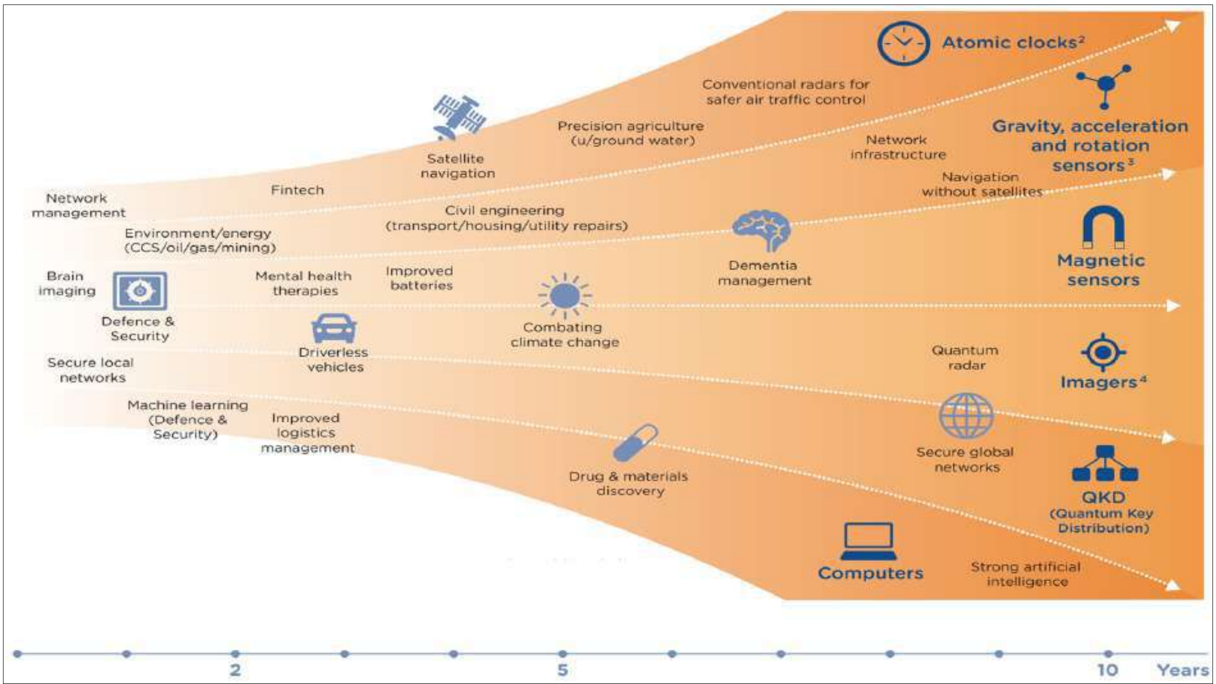


Figure I.2: A Quantum Technology Roadmap (Estimates of First Use by Industry) [CREDIT: UK Quantum Strategy [903]]

Quantum computing

Quantum computing is part of a broader suite of challenges under the general banner of Quantum Information Science. Quantum Information Science (QIS) covers the R&D of quantum computers, algorithms, cryptography, programming languages, modelling, simulation, and knowledge applications. Research in quantum computers has focused on quantum error correction, noise reduction, logic gates, and exploring various qubit technologies. Photonics and semiconductor methods for room-temperature quantum computing have made great strides. Numerous companies and institutions are working towards developing thousand-qubit systems by 2023 and million-qubit systems by 2029. Related developments of interest are the research on quantum machine learning and the widely available (free but limited) access granted by several companies to quantum computing resources.

Quantum computing relies on well-developed, although non-intuitive, physics. That said, the en-

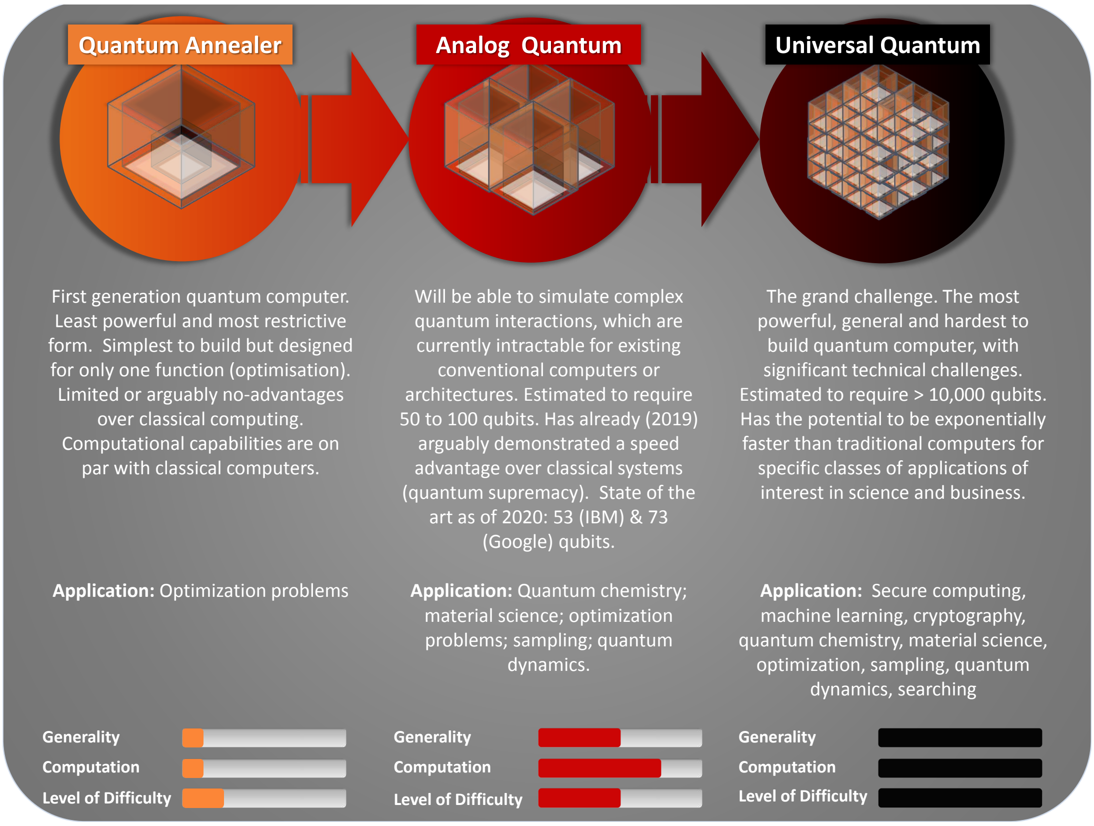


Figure I.3: *Three Types of Quantum Computers [CREDIT: Adapted from [904]]*

gineering challenges of quantum computing remain extreme despite the considerable progress already made [905]. The PRC, Google, IBM and many Alliance nations are investing heavily in a quantum race to develop specialised (e.g. optimisation through quantum annealing) and general-purpose quantum computers capable of demonstrating a real and significant advantage over classical supercomputers. Over the last two years, the number of qubits has grown from 54 to 433, with 1000+ qubit systems on track for delivery next year and million-cubit systems by 2030 are planned. This is an impressive technical feat, but future designs face significant scaling, noise, cross-talk, stability, and commercialisation challenges. It is a long journey to a million-qubit system needed to solve substantial problems. Investment and research challenges are significant. Given the current economic climate, hype, and the need for an eventual return on investment, it has been suggested that we are at risk of a *"quantum winter"* [906, 907]. Further, the hype around quantum is not necessarily good for research that seeks to expand our understanding of the quantum realm.

Quantum computing research is being driven predominately by commercial interests. While special-purpose *quantum computing devices* may be available in the mid-term, developing a true general-purpose *universal quantum computer*, applicable to a range of NATO problems, is likely a long way from being commercially available. As per [884], experts estimated that such a quantum computer might be built within the next 15 to 50 years. In the medium term, developing new quantum-optimised algorithms and M&S for defence problems may be applied to special and limited *Data* or BDAA problems. A promising approach to improving the short-term utility of quantum computers is to focus on using Noisy Intermediate-Scale Quantum devices (NISQ) [153, 908, 909, 910, 911].

Nevertheless, new approaches such as nitrogen-vacancy or photonic systems, in contrast to ion traps or superconducting qubits approaches, are promising larger, more stable systems. Even if there is a "quantum winter", quantum computers may eventually be developed for practical application, although it may take longer than the forecasted ten years. At this point, it is still being determined whether quantum computing will follow the path of energy production by nuclear fusion, e.g. always 20 years away. At the same time, disappointment may also set in as the limitations of such systems and the limited sub-set of problems/algorithms that can successfully employ quantum computing become apparent. Even the application of current methods to challenges of materials modelling (a role for which such systems were originally suggested) has so far been disappointing. As such, it must be noted that investment in quantum computers must not replace investment in classical supercomputing technologies. If quantum computing is to be successful, it will likely be as a specialised co-processor as part of a supercomputer system.

Regardless, quantum computing holds incredible promise to revolutionise science itself. Quantum simulations, which accurately model atomic level many-body systems, may be able to predict material behaviours from first principles. This capability would allow the straightforward design and creation of new materials with specific desirable physical properties, such as ultra-hard armour, superconductivity, high-temperature tolerance, etc. Similarly, the potential application of quantum computing to AI/ML [912] would enable and empower new Quantum ML (QML) algorithms.

Quantum communications

In contrast to quantum computers, quantum communication is developing at an impressive rate in the near term. Real-world demonstrations of significant terrestrial and space-based systems have occurred, and the technical challenges appear surmountable. This promises the development of highly secure global communications. Some have suggested (e.g. US DOD) that developing quantum communication technologies is unnecessary as there are reliable, well-understood methods for ensuring secure communications even in a post-quantum computing world. Next-generation post-quantum encryption techniques already exist and await verification (e.g. to ensure that classical and quantum methods cannot break them), standardisation and widespread implementation. Further, given their limitations and costs, quantum communication networks will augment, rather than replace, existing networks.

The development of a quantum internet holds great promise [913, 914, 915, 916, 917]. However, it has also been described as a solution to a problem no one has asked to be solved and of little value for most internet communication [918]. The quantum internet is expected to leverage quantum computers and communication networks to create an ultra-fast and highly secure internet suitable for the big data challenges expected over the next 20 years [919, 920]. Essentially this allows communication of not only the output of a quantum computation but live updates of still entangled qubits [921]. Since this relies heavily on quantum computing, developing a quantum internet is not a foregone conclusion.

Quantum communications and cryptography (often considered a sub-area of QIS) exploit many technologies for ultra-secure communications (e.g. intrusion detection and low probability of intercept). Examples of maturing technologies include QKD (quantum key distribution) and quantum random number generators (QRNG). Using these and other related technologies will ultimately enable a secure quantum internet. Post-quantum encryption methods, such as Super-singular Isogeny Diffie–Hellman key exchange

(SIDH), promise to establish a secret key between parties over an otherwise insecure communication channel. Quantum communications advances are essential in developing effective 6G technologies [922].

Quantum communication capability (for ultra-secure channels) is an important research area, but it is often driven by strong commercial and intelligence interests. The use of near-term QT may enable the detection of an eavesdropper on a communication channel. Further development of quantum key distribution (QKD) and quantum post-quantum encryption options will provide the Alliance with superior encryption capabilities. In the mid-term, investment should focus on QT optical communications for anti-eavesdropping capabilities and as a defence against jamming to enable the Alliance to understand vulnerabilities and opportunities. In the long term, a global-reach quantum entanglement distribution system should be developed to support secure communications and other advanced QT applications.

The PRC, in particular, has taken a leadership role in developing quantum communications. For example, *"Chinese scientists have established the world's first integrated quantum communication network, combining over 700 optical fibres on the ground with two ground-to-satellite links to achieve quantum key distribution over a total distance of 4,600 kilometers for users across the country."* [923, 924].

Quantum sensing

Of all the quantum technologies, sensors are the most well-developed, enabling precision measurements of physical quantities such as atomic energy levels, photonic states, and spins [925]. Moreover, quantum sensors may greatly exceed their classical counterparts with substantially increased precision, mapping magnetic, electric, and gravitational at exquisite resolutions. Nevertheless, SWaP-C challenges are considerable and will limit the fielding of such sensors.

Examples of quantum sensors are:

- **Atomic clocks**: Positioning, navigation, timing, networking and metrology [926, 927, 928, 929];
- **Atom interferometers**: Gravimeters and accelerometers [930, 931, 932, 933];
- **Optical magnetometers**: Bioscience, geoscience, ASW and navigation [934, 935];
- **Quantum optical**: Local and remote sensing, networks, basic science [936, 937]; and
- **Atomic electric field sensors**: GHz-THz radiation detection [938, 939, 940].

Quantum sensors employ quantum systems, properties, or phenomena to measure physical properties with exceptional precision and high sensitivity [941]. Such sensors include superconducting quantum interference devices (SQUID), magnetic resonance imagery, positron emission tomography, atomic clocks, atomic vapours, nitrogen-vacancy magnetometers, atom interferometry, spin qubits, trapped ion and flux qubits, and fibre Bragg scattering. Of all the quantum technology areas, quantum sensors are the most near-term in their application.

Some example application areas are all-weather, day-night tactical sensing for Intelligence, Surveillance, Targeting and Reconnaissance (ISTAR), and strategic (long-range maritime, air and space) surveillance. These systems will improve Anti-Submarine Warfare (ASW) capabilities and support the development of hitherto impractical low power high, sensitivity airborne and space-based sensors. In addition, quantum sensors are potentially more resistant to jamming [576].

Quantum sensors are a broad grouping comprising various instruments for specific physical measurements or applications, including gravity and inertial forces, photonics (visible light and infrared), RF, electric field, magnetic field strength, acoustics, stress, pressure and temperature (e.g. via fibre Bragg) [943]. Their maturity depends on the sensor type and the entire sensor system. Single sensors are more advanced than sensor arrays. Complex data inverse problems and associated computational costs, such as gravity, also challenge imaging. Areas of application to note are:

- **EM Sensing:** The STO Centre for Maritime Research and Experimentation (CMRE) carried out preliminary research and a study on the application of the latest generation of quantum magnetic

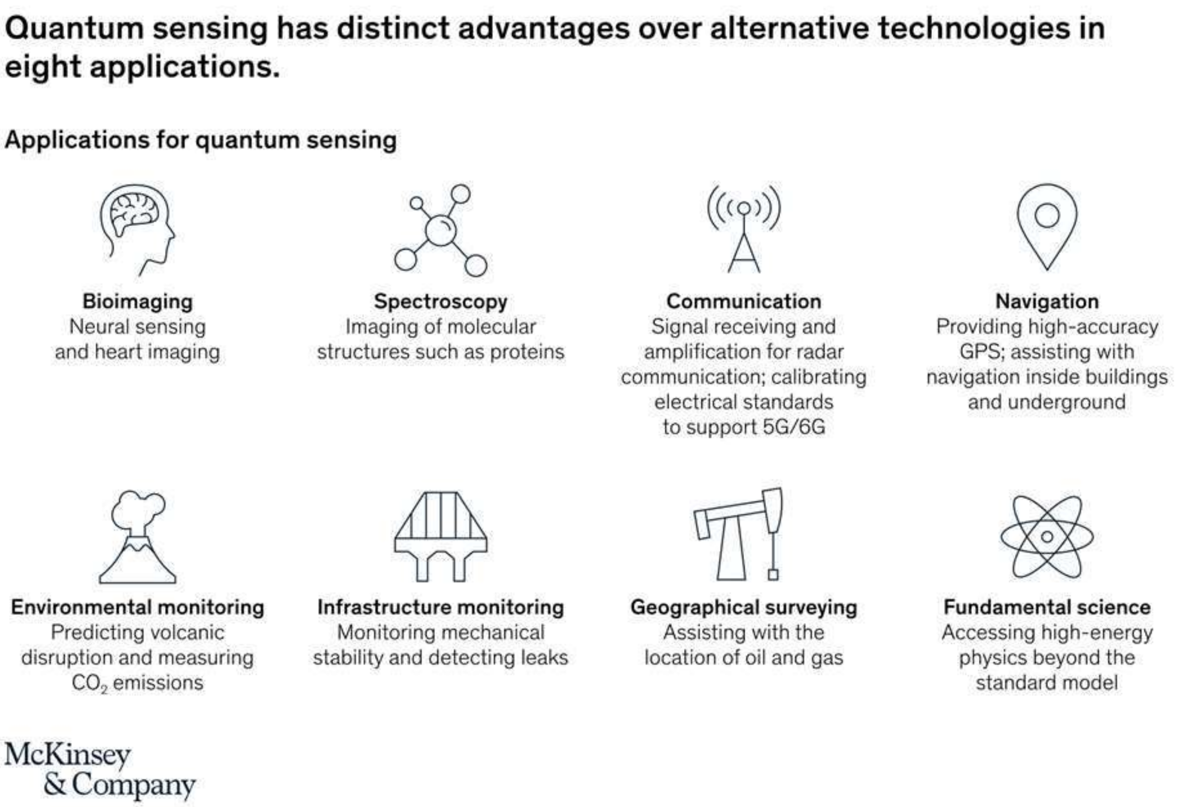


Figure I.4: *Examples of Quantum Sensing (CREDIT: McKinsey & Company [942])*

sensors for anti-submarine warfare (ASW) applications, with funding by NATO Allied Command Transformation (ACT). As one of the study outcomes, three types of novel quantum magnetic sensors were selected for ASW applications because of their unique SWaP-C advantages and improved sensitivity. Such sensors could be readily deployed at the sea surface on small uncrewed surface vehicles, uncrewed aerial vehicles, autonomous underwater vehicles, or portable bottom sensors as a network to detect magnetic objects such as submarines.

- **Gravimetric:** The current technological maturity of gravimetric sensors (sensitivity, lightness, robustness, and compactness) does not allow use on mobile platforms. However, atomic interferometric approaches show considerable promise. Gravity sensors will be most useful in supporting navigation (via gravity maps) and mapping underground structures (tunnels, urban infrastructure).

- **Imaging:** Research into using quantum illumination for imaging is still at an early stage of development, [944, 357].

- **LiDAR:** A recently completed Technology Watch activity on quantum LIDAR (Light Detection and Ranging) states that different aspects are maturing on different timescales, some of which can be exploited immediately. In contrast, others will take decades to emerge from the laboratory [945]. Therefore, it was concluded that quantum LIDAR is an aspirational, longer-term goal for sensing capabilities, although the technology developed on-route will likely have short-term benefits for defence. However, quantum LIDAR exploiting quantum entanglement is a significant technical challenge.

- **Radar:** Quantum radars will be many times more sensitive than current systems. Nevertheless, quantum radars are of limited value for defence and security given the current operational limitations, and technical challenges [944]. Nevertheless, this is an area of sensor development suitable for further exploration [946, 947].

- **Vector Imaging:** Recent development has stimulated interest in highly sensitive vector magnetometers for full tensor gradient sensors. Such sensors have many potential applications, such as magnetic anomaly detection, ASW, IED detection, magnetic navigation and mapping of underground service systems [153].

- **Naval Mine Detection:** Quantum Sensors combined with quantum PNT promise to improve the detection of naval mines.

- **Quantum Remote Sensing**: Quantum remote sensing, such as quantum radar [898, 899, 899] has the potential to make stealth technologies obsolete, provide more accurate target identification, and allow covert detection and surveillance. There are two known approaches to quantum-enhanced remote sensing: quantum interferometry and quantum illumination. Both rely on using entangled photons and retaining one half of an entangled photon pair while sending the other out (in a known direction) to interact with the environment. These sensors will enable much more accurate and sensitive measurement and much lower power for applications such as detecting and tracking small, stealthy targets. Developments will rely on several quantum engineering capabilities, such as the controlled generation of individual entangled photon pairs, the ability to retain one of each pair in isolation and to detect the returning photon for comparison with the idler.

- **Magnetic and Gravity Sensing**: Precise magnetic field measurements are used by maritime patrol aircraft to localise submarines, using MAD (magnetic anomaly detection) sensors. Current sensors are unsuitable for small UAVs due to size-weight-power constraints, but emerging quantum technologies may provide a solution. There are also special applications of gravity sensing that could be enabled by quantum technology for specialised surveillance applications, such as underground structure detection (tunnels, bunkers) from an airborne platform.

One particularly interesting application has been the development of PNT systems. Quantum PNT describes the use of quantum sensing to support precision navigation and accurate timekeeping in GNSS-denied environments. It also includes various methods for hyper-accurate timekeeping (e.g. femtosecond precision) that are important for communication and S&T development.

The PNT market has been forecasted to reach 200 million USD by 2024. Developments are ongoing, but the critical SWaP-C challenges are the most vital, especially as they will enable UxV operations and navigation systems for large mobile military systems. Significant progress has been made in developing deployable systems, with early systems being field trialled by groups such as the Office of Naval Research [948].

There are two fundamentally different approaches to PNT: one involving the transmission and receipt of external signals, such as GPS, and the other relying on the self-contained sensing of motion, such as those provided by inertial systems. Since the future security environment anticipates a highly contested electromagnetic environment (jamming and spoofing), NATO must be prepared to operate in a GPS-denied environment. Investment in QT will enhance resilience to these emerging vulnerabilities. Quantum technologies are expected to support the combination of ultra-precise time measurements with ultra-precise acceleration and angular rotation measurements (each of which uses a different quantum technology) to provide ultra-precise inertial navigation (and timing), which will be needed as GPS, and other signal-dependent means become unavailable due to countermeasures (or inside structures). Several competing concepts exist (solid-state nitrogen vacancy, atom trapping in free space, cold atomic interferometry, etc.). Developing cold-atom QT will enable resilience to Global Navigation Satellite System (GNSS) denial through smaller QT clocks. In addition, gravity and magnetic sensing could be used to georeference using survey maps. It is expected that PNT will be first fielded through rack-mounted units (e.g. desktop computer size), suitable for exploitation on larger mobile military systems, e.g. ships. With continuous investments in the mid and long term, the systems are expected to reduce in size, weight, power and cost and ultimately provide navigation better than current GNSS performance, with greatly reduced reliance on external references.

Quantum PNT will be an important application area for quantum sensors in NATO. Such effects support the development of very finely tuned precision instruments for PNT. In addition, PNT technologies will enable operations in GNSS-denied or other challenging operational environments (e.g. long-duration submerged under-ice autonomous operations). The challenges in developing quantum PNT are miniaturisation, robustness, power, and weight, i.e. SWaP-C. Quantum PNT is an area with a potential near-term impact on defence and security capabilities [944, 357].

Developments to note are:

- **Navigation Systems** will be a critical enabler of operations in GNSS-denied environments. Near to medium-term quantum navigation systems will enable rack-mounted units suitable for exploitation on larger mobile military systems (e.g. large naval vessels).
- **Atomic Clocks** were demonstrated in the lab a decade ago, but the challenge is to produce miniature devices integrated into current systems. Low power, weight and ultra-stable systems are being developed to support UxV operations.
- **Quantum accelerometers** for inertial navigation will offer an order of magnitude over more traditional piezo electrical (IEPE/ICP) accelerometers.
- **Interferometric Fibre Optic Gyros (IFGOS)** may allow more performance and portability thancold atom gyros.
- **Gravimeters and gravity gradiometers** based on atom interferometry could enable airborne detection of tunnels, identification of nuclear materials, gravity-aided navigation and geodesy.

TRL for quantum sensing is still quite low; however, several enabling technologies are advancing rapidly and may be available in the mid-term to address NATO ISR challenges. Improved sensors may be used to build georeferenced global gravitational and magnetic anomaly maps. Near-term targeted investments in QT gravity, magnetic and EW sensors could demonstrate new military capabilities for tunnel surveys, magnetic anomaly detection and electromagnetic sensing. In the mid-term better QT sensors will enable these capabilities to be deployed in more challenging military environments such as space. In the long term, using entanglement distribution networks may make distributed sensors thousands of times more precise than is currently available. An order of magnitude performance improvement is necessary for some applications (GNSS-denied navigation, missile guidance), but achieving this TRL 8 target is expected to take 5 – 10 years.

On a practical level, the D3TX [33] demonstrated limited usage of the Quantum Sensors Technology Card in all four rounds of gameplay. Whilst rarely chosen, the benefits of quantum sensors were recognised by those groups that selected them, citing their sensitivity, accuracy, and security. However, the challenge of the robustness and scalability of current quantum sensor technologies to cover multi-mission roles was also recognised.

Military Implications

BLUE

Many defence applications exist for next-generation quantum technologies [949, 876, 883, 877, 951, 952, 953, 954, 882, 878, 950]. The following subsections summarises some of the more interesting areas.

Enable

The development of a quantum internet would allow ultra-secure strategic communication and the secure sharing of quantum computing resources. This, in turn, would enable better strategic assessments and geostrategic responses (e.g. using quantum game theory [955, 956] and improved modelling and simulation).

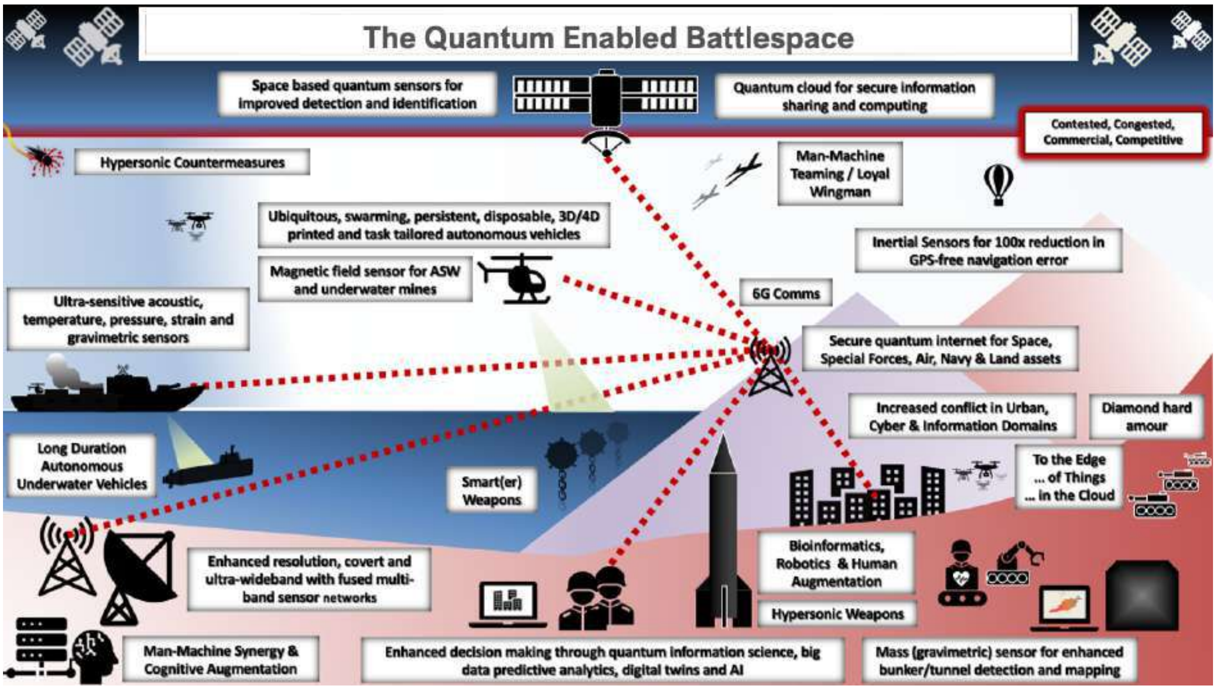


Figure I.5: *Quantum Technologies in the Future Battlespace.*

Prepare

Quantum computing may enable better optimisation and AI/ML support in the preparation phases. In addition, space and terrestrial quantum sensors will also improve battlefield data collection and intelligence preparation.

Sustain

Quantum computing may enable better optimisation and AI/ML support to the sustain phase, particularly optimal logistics support. Furthermore, improved and embedded quantum sensors will also support improved maintenance and the development of digital twins.

Engage

Highly sensitive quantum sensors and communications will increase the effectiveness of the kill chain through support for multi-domain targeting and low-observable communication with weapon systems. Quantum PNT will support operations and targeting in GNSS-denied environments and increased precision. Quantum neural networks will increase weapon systems and autonomous vehicle effectiveness. The use of quantum gravimetric and magnet anomaly detectors may be highly disruptive for ASW operations and subterranean warfare.

Protect

Quantum computing and simulation may support the development of designer materials with reduced weight, increased strength, and improved ballistic, energy, and chem/bio-defensive characteristics.

Inform

Quantum computers are expected to provide better computational capabilities beyond the theoretical limit of classically designed computers for **specific** classes of analytical problems (e.g. optimisation and simulation). This computational leap will enable highly sophisticated approaches to the encryption and decryption of codes, rendering current cryptographic methods obsolete. Furthermore, sophisticated and rapid M&S will enable complex operational and organisational decision-making, new ways of developing hitherto undiscovered Materials and Biotechnologies, and next-generation AI (e.g. quantum neural networks for target and image identification problems).

Quantum sensors will be many times more sensitive than current systems. This will support the development of counter-stealth and covert radars [899, 957]; magnetic, acoustic and gravity sensors with greatly increased ASW capabilities [897]; and support the development of hitherto impractical low power high sensitivity airborne and spaced based sensors. Some example applications are for all-weather, day-night tactical (battlefield etc.) sensing (short-range, active/passive, covert, using EO/IR/THz/RF frequencies) for ISTAR, as well as strategic (long-range maritime, airspace, space) surveillance (active, RF). Quantum sensors are potentially more resistant to jamming.

Quantum effects support the development of very sensitive precision instruments for PNT. Such PNT technologies will enable operations in a GPS-denied or difficult operational environment (e.g. long-duration submerged under-ice autonomous operations). In the near to medium term, rack-mounted units suitable for exploitation on larger mobile military systems (e.g. ships) will be available.

C3

The development of *unbreakable* cryptography and the ability to decrypt encoded messages using current cryptographic methods will provide significant challenges for current C4ISR systems.

RED

Within the 2023-2043 time frame, the primary threat is from near-peer competitors, especially given the high mathematical sophistication and R&D investment required. In addition, the potential security implications due to the loss of useful encryption methods, the loss of air and underwater stealth, and a possible RED analytic/decision advantage enabled by quantum computing will challenge Alliance operations.

Interoperability

Next-generation quantum technologies will present significant interoperability challenges, primarily driven by differing investment rates and national security considerations, given the potentially dramatic improvements in sensing and communication capabilities.

S&T Development

State of Development

This section addresses the state and science development rate in the quantum fields. Further, it answers the question: What does quantum mean for developing related scientific areas, or what synergistic relationship does it have with these NATO S&T Priorities? Next-generation quantum systems are expected to be especially effective as they provide increased computing capabilities, support for novel algorithms, improved sharing of information resources, more secure communication and increased precision and accuracy [883].

Data

Developments in next-generation quantum technologies will directly influence the outcome of *Data* R&D by providing faster-specialised processing supported by more accurate and abundant data. In addition, quantum computing will drive developments in data storage. In contrast, quantum communications (and quantum networks) are considered a potentially critical aspect of 6G and beyond wireless communication technologies [958].

AI

Many problems in machine learning may be described in terms of optimisation [959]. Quantum computers are well suited to solving such issues and, as such, will enable improved training and development of AI/ML systems [960]. Further, improved quantum sensing technologies (e.g. quantum LiDaR) will provide more accurate data, such as position and timing.

RAS

As quantum technologies will support developments in AI, these developments will support increasingly sophisticated UxVs AI. Quantum computers are well suited to solving such problems and, as such, will enable improved training and development of UxV AI/ML systems. Further, improved quantum sensing technologies (e.g. quantum LiDaR) will provide more accurate data, such as position and timing.

Space

Space technologies will be impacted in three critical ways. First, novel materials, designed to order based on direct quantum simulation and analysis, will potentially be stronger, lighter, flexible, and resilient. This, in turn, may support the development of novel launch systems or more energy-efficient orbital vehicles. Second, using quantum sensors, with greatly improved sensitivity, will improve space-based data collection, including increased use of passive sensors. Finally, space-based quantum communication (already demonstrated) requirements will improve inter-satellite communication security and increase demand for more space-based communication systems supporting a quantum internet [961].

Hypersonics

Hypersonic technologies will primarily be influenced by the potential development of quantum-engineered bespoke materials designed to be more head resistant, stronger, lighter, flexible, and resilient. In addition, quantum computing may also support more accurate airflow models, thereby increasing the effectiveness and efficiency of hypersonic systems.

Energy

Quantum computing and the simulation and modelling it supports may allow for designing new and improved battery materials and fuel chemistry. It may also support the modelling and simulation of fusion or novel energy solutions, increasing the likelihood of a disruptive technological breakthrough [962, 963].

E&EM

Quantum computing and the simulation and modelling it supports may allow for designing new and improved electronic technologies and associated materials.

Material

As noted above, whether for space, hypersonic systems, energy, or electronics, the use of quantum simulation to support the development of bespoke materials has the potential to be highly disruptive [964, 965]. Further, using non- or minimally invasive quantum sensors will improve our understanding of material performance and behaviour.

BHET

Understanding biological processes (such as protein folding [966]) will be greatly enabled through quantum computation. Further, non- or minimally invasive quantum sensors [964] will improve our ability to understand and monitor biological processes.

STO Activities

Several STO Scientific and Technical Committees have produced significant research on Quantum technologies. Many panels have ongoing activities on several topics aligned with these technologies. The following is a sample of ongoing activities:

- AVT-377: Introduction to Quantum Computing in Fluid Dynamics
- IST-ET-117: Data Hiding in Information Warfare Operations
- IST-SET-198: Quantum Technology
- SAS-159: How Could Technology Development Transform the Future Environment
- SET-264: Quantum Position Navigation and Timing for NATO Platforms
- SET-289: Nanotechnology for Optics & Infrared Photo Detection
- SET-ET-132: Quantum Algorithms for Data Fu-

sion and Resource Management

- SET-ET-133: Elaborating TAPs on Quantum Technology within STB topical CPOW
- SET-322: Evaluation Framework for Multi-sensor Tracking and Fusion Algorithms (working on quantum algorithms)
- SET-137: Quantum Structures for non-cryogenic infrared imaging

Scientometric Analysis

Keywords associated with Quantum Technologies (QT) as derived from STEAM analysis are shown in Figure I.6.

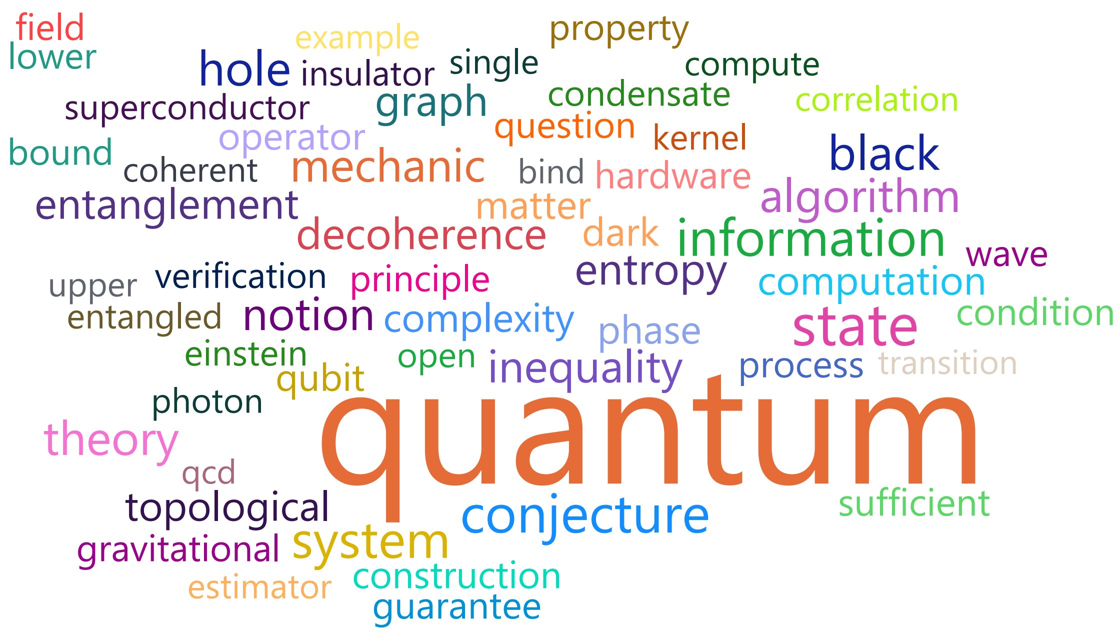


Figure I.6: *STEAM - Quantum - Keywords*

Survey Results

The following table presents the assessed potential impact, state and rate of development, and identified areas for focused research.

Table I.1: *Quantum Technologies (QT) 2023 - 2043.*

EDT	Technology Focus Areas	Impact	TRL	Horizon
Quantum	Communications	High	3-4	2030-2035
	Information Science & Computing	High	3-4	2035 or (+)
	Sensors	High	3-4	2035 or (+)

Conjecture Card: Quantum Technologies

A. Transparent Ocean  Obtain the position of any submarine, at any depth, everywhere on Earth, through ultra-sensitive magnetic, gravity or acoustic sensors.	**B. Quantum Cryptography**  Crack certain types of encryption in microseconds. Overcome cyber defences to disrupt or destroy others' computer systems.	**C. Quantum Radar**  Use air and space-based covert ultra-sensitive very low-power radar systems to track and identify air targets at the extreme line-of-sight ranges.
D. Computational Dominance  Utilise novel quantum algorithms (optimisation, neural networks, etc.) to provide a decision edge supporting military and enterprise operations and functions.	**E. GPS Denied Environment**  Operate for weeks in a GPS-denied environment with complete geospatial and temporal awareness equivalent to today's GPS systems at sea, in the air or on land.	**F. Precision Navigation**  Conduct under-ice precision navigation with unmanned underwater vehicles for months, without GPS updates, in the deep ocean and littoral areas.
G. Quantum Illumination  Short-range, very low-power non-invasive imaging for security or biomedical applications.	**H. Quantum Communications**  Communicate instantaneously at long range without being prone to eavesdropping.	**I. Chemistry & Materials**  Simulate the quantum structure and behaviour of new chemicals and materials to create new biochemicals and materials important for CBRN countermeasures.
J. Subterranian Mapping  Precision sensors allow for high-resolution mapping of underground structures.	**K. Quantum Game Theory**  Quantum game theory supports new approaches to strategic deterrence.	**L. Quantum Neural Networks**  Quantum neural networks supports a revolutionary leap in AI effectiveness.

J. Space Technologies

NATO Space

"We consider that attacks to, from, or within space present a clear challenge to the security of the Alliance, the impact of which could threaten national and Euro-Atlantic prosperity, security, and stability and could be as harmful to modern societies as a conventional attack. Such attacks could lead to the invocation of Article 5. A decision as to when such attacks would lead to the invocation of Article 5 would be taken by the North Atlantic Council on a case-by-case basis." - *NATO Brussels Summit Communique (2021)*.

Definition

Space Technologies

Space is the 'volume' beyond the upper limits of airspace. *Space Technologies* exploit or must contend with the unique operational environment of space, which includes: freedom of action, global field of view, speed, freedom of access; a near-vacuum; micro-gravity; isolation, and extreme environments (temperature, vibration, sound and pressure). *Space systems* can include: (1) the space segment (all elements in orbit); (2) the ground segment (ground station and command and control centre); (3) the data links (uplink, downlink and cross-link); and (4) the user segment (decision-makers and deployed forces). *Space capability* are those capabilities using space systems, which support, among others, military commanders, staff and forces in all operational domains [967].

Keywords

ASAT (Anti-Satellite) · Cislunar · Constellations · Counter Satellite · Debris · Deterrence · Electronic Warfare · Kinetic · Launch · METEOC (Meteorology & Oceanography) · Platforms · PNT (Position, Navigation and Timing)· Propulsion · Satellites · Sensors · SEW (Space Electronic Warfare) · SSA (Space Situational Awareness)

Developments

Overview

Space is increasingly important for NATO Allies' **prosperity** and **security**. The world's economies, militaries, and societies rely heavily on space-based systems, and that reliance is making the space domain more competitive, congested, and contested than ever before. The number of space-faring nations has rapidly increased in the past decade [968], and nowadays, more than 80 countries have at least one registered spacecraft in orbit [969]. The continued explosion of commercial interest in space is already a reality, and this continued growth is the biggest *space* development foreseen over the next 5-10 years.

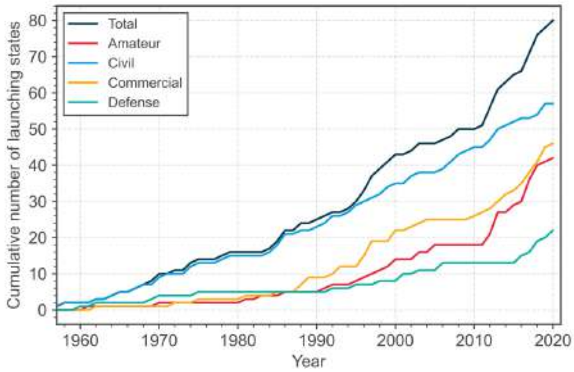


Figure J.1: *States with at least one registered space object over time by category (CREDIT: [969]).*

As of the publication of this report, the number of operating satellites is 5465 [970], a number driven in no small measure by the exponential decay in per kg launch costs [971] and the increased affordability of space components [972]. Moreover, the number of active orbiting space objects has tripled since 2020 [970]. With all this activity, by 2040, the global space industry is forecasted to grow from $469 Billion (US) [973] to $1 - 2.7 trillion [974]. This growth in the space economy will be driven by a shift of the space business model from **old space** into **new space**. New space actors are investing in technologies such as satellite launch (e.g. Space X and Blue Horizon); satellite internet (e.g. OneWeb, Amazon, Space X); satellite communications; deep space exploration (e.g. James Webb telescope); lunar landing (e.g. Project Artemis); earth observation; asteroid mining (e.g. iSpace); space debris removal; space tourism (e.g. Space X and Blue Horizon); space research; and space manufacturing [974]. These rapid developments will make NATO Allies dependent upon space capabilities to conduct missions responsively and efficiently.

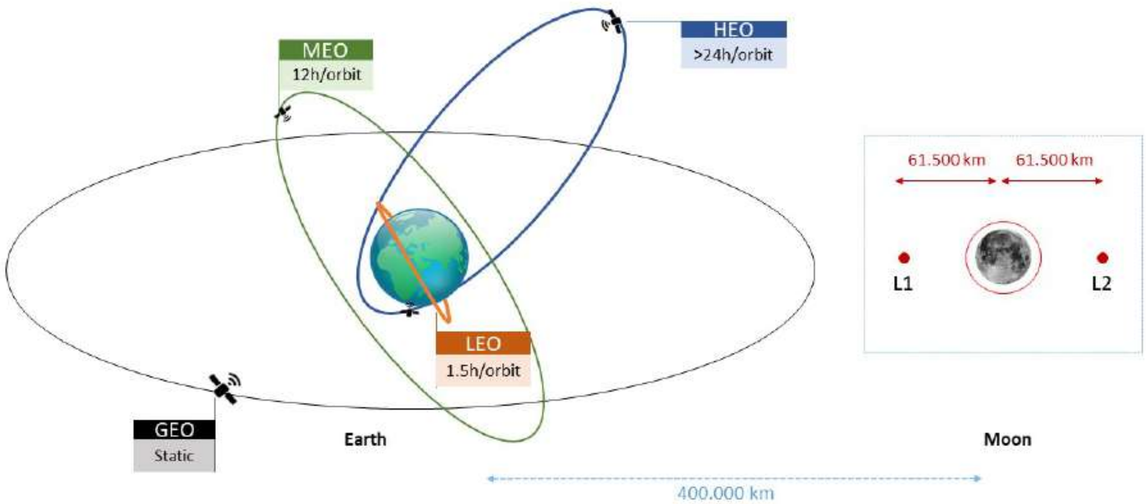


Figure J.2: *LEO, MEO, GEO, HEO orbits*

The increased reliance on space technologies for civilian and military use encourages nations to protect critical space-based assets. In this sense, many countries have declared space a war-fighting domain (e.g. Russia, China, and the United States). They are focusing on developing offensive and defensive space capabilities [975], which translates into an increased risk of the weaponization of the space domain [976]. This risk includes the use of anti-satellite (ASAT) (hard or soft kill) weapons [977, 978], which have the potential to *pollute* the near-earth environment, significantly increasing the risk of collision with space debris. The Prevention of an Arms Race in Outer Space (PAROS) is an active topic amongst the

Table J.1: Orbit Definitions

Orbit	Altitude	Uses
Low Earth Orbit (LEO)	Up to 2,000 Km	Communications/ ISR/ Human Spaceflight
Medium Earth Orbit (MEO)	Between 2,000 to 20,000 Km	Communications/ PNT
Highly Elliptical Orbit (HEO)	Perigee: Up to 2,000 Km Apogee: Approx. 40,000 Km	Communications/ ISR/ Missile Warning
Geosynchronous Earth Orbit (GEO)	Approx. 36,000 Km	

international community [979]. The body of international law that governs space activity declares that *"the Moon and other celestial bodies shall be used exclusively for peaceful purposes"* and explicitly forbids the use of weapons of mass destruction [980]. However, these international norms are still vague and leave room for interpretation. In the past few years, some nations have aimed to reduce that ambiguity by developing internationally accepted standards of responsible behaviour within space [979, 981]. At the Brussels Summit in July 2018, NATO leadership acknowledged that space is a highly dynamic and rapidly evolving area essential to coherent Alliance deterrence and defence. A little over a year later, in December of 2019, NATO defence ministers recognized space as a new operational domain – alongside air, land, sea and cyberspace [982]. In 2022 NATO published an overarching Space Policy [967] that defines the Alliance's approach to space and synthesizes its core space capabilities [983] outlined in Table J.2.

Table J.2: NATO Space Capabilities and Usage.

Space Capability	**NATO Use and Effects**
Position, Navigation, Time (PNT) & Velocity	Precision Strike Force Navigation Support to Personnel Recovery (PR)/Combat Search and Rescue (CSAR) Network Timing
Integrated Tactical Warning and Threat Assessment	Force Protection Attribution Missile Warning
Environmental Monitoring	Mission Planning Munitions Selection Weather Forecasting
Communications	Command and Control Unmanned Aerial Vehicle Ops Beyond-the-Horizon communications
Intelligence, Surveillance and Reconnaissance	Coverage of Operation Execution (in the operations centre) Battle Damage Assessment (BDA) Intelligence Targeting

Finally, S&T has a strong interest in space technologies and the use of space, but many aspects are beyond the scope of this report as they fall outside of NATO's defined areas of concern. These include services or technologies more aligned with the civilian sector or national interest, including (heavy) launch, astronomy, planetary exploration, surveillance of space, and human spaceflight. For this appendix, space technology is understood to encompass five main areas of R&D activity which are seen to be disruptive:

Propulsion and Launch

The expected increase in the number of orbiting spacecraft, the need to reduce launch costs and the effort to decarbonize the planet is empowering the development of innovative propulsion systems [984] to replace conventional rocket propellants. The need for rapid launch capabilities has grown with the increased utility of small-sats (cube, nano, pico, etc.) coupled with the increasing risk of a contested space environment and terrestrial anti-satellite weapons [985]. Mission-tailored systems are envisaged with development times in weeks, not years... Most launch systems are incapable of such rapid turnaround or providing on-the-spot (e.g. on the order of hours) in-theatre launch. However, in the last couple of years, we have seen the successful development of *more efficient* reusable launch systems (e.g. Space X Falcon 9), which are helping to bring down the cost of space exploration. In the next decades, electrical pump-feed rocket engines (e.g. Rocket Lab Electron) or magnetic rocket thrusters will reduce strategic dependency on heavy propellants and increase efficiency [986]. New systems such as the versatile new generation engine that will allow a vehicle to operate and manoeuvre both in the air and in space [733], or kinetic-launch systems [987] (see Figure J.3) will increase the ease of access to this domain by bringing down launch costs even lower.

Figure J.3: *Kinetic-launch Accelerator (CREDIT: [988])*

Smallsats (e.g. Starlink constellation) and other space systems already benefit from electric thrusters that allow for the extension of their operational life-cycle [989] and increase their manoeuvrability to avoid space debris collisions or changing orbits [990]. Also, developing more advanced electric propulsion systems or innovative solutions such as photophoretic levitation and propulsion mechanism [991] will allow conducting operations on Very Low Earth Orbit (VLEO) by enabling systems to overcome the problems caused by aerodynamic drag. VLEO (e.g. below 450 Km over the Earth's surface [992]) presents several benefits compared to higher obits, especially for remote sensing or optical imaging. Also, R&D on propulsion systems will be key for developing **cislunar operations** and beyond [993]. Even if nowadays most human space activity occurs relatively close to Earth (Low, Medium and High Earth Orbit), we can begin to detect weak signals (e.g. NASA's Artemis mission, the Chinese objective to set up an International Lunar Research Station by 2030) which will bring more attention to this domain in the upcoming years [994, 995]. The US Space Force (USSF) and NASA recently signed a Memorandum of Understanding acknowledging the increasing importance of cislunar and expanding the USSF's surveillance tasks to this domain [996]. Cislunar Space is interesting economically (e.g. water, Helium-3, rare Earth metals) and operationally. This new domain will offer new orbit trajectories (e.g. Lunar orbits; Earth-moon Lagrange Points) that could be leveraged to sustain upcoming lunar activity but could also be useful for supporting terrestrial activities (e.g. Space debris monitoring). However, this new type of operation will require developing more advanced and new in-space propulsion systems. There is ongoing research for the development of more advanced nuclear propulsion systems such as nuclear thermal [997, 998] (e.g. DRACO Program [999]), solar [1000] or chemical [1001], and new propulsion architectures such as Pellet-Beam propulsion to sustain heavy load cislunar and deep-space operations [1002]. At the same time, solar sail propulsion systems may power smaller spacecraft while providing long-duration but low-thrust propulsion alternatives.

Platforms

Operating predominately in low-Earth (LEO) and medium-Earth (MEO) orbits [969], **Small satellites (Smallsats)** are spacecraft which are less than 500 kg in mass and encompass several subcategories, including [1003]: (1) *minisatellites* (100 - 180 kg); (2) *microsatellites* (10 - 100 kg); (3) *nanosatellites* (1 - 10 kg); (4) *picosatellites* (0.01 - 1 kg); and, (5) *femtosatellites* (0.001 - 0.01 kg).

Smallsats deliver affordable science and services to academia, commerce and government. In addition, active individual satellites and entire constellations can be deployed at greatly reduced costs in capability areas such as communications, extended ISR, and geographical positioning [1004]. This will create new opportunities for military decision-makers. Indeed, smallsat constellations will provide faster revisiting rates and enhanced space resilience. For example, in February 2022, Space X was able to redirect its Starlink satellite constellation to provide broadband connectivity to Ukraine to overcome the Russian network disruption (see figure J.4).

(a) *(b)*

Figure J.4: *Starlink Deployment*

Around 18,000 smallsats will be launched between 2022 and 2031, and 81% are expected to be part of constellations of hundredths or thousands of satellites [1005]. This will be possible thanks to reduced costs associated with access to space due to a decrease in launch fees [971] and the increasing affordability of space platforms. In addition, ongoing research on *commoditized satellite buses* [1006] will allow dozens or hundreds of different types of satellite payloads to operate in low-Earth orbit [1007]. In the context of NATO, smallsats could support three of NATO's strategic capabilities: (1) strategic information dominance; (2) reliable, secure communication; and (3) enhancement of space domain awareness.

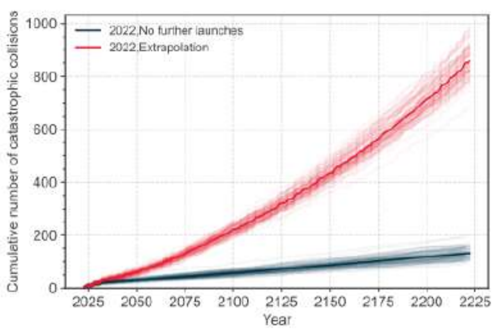


Figure J.5: *number of cumulative collisions in LEO in the simulated scenarios of the long-term evolution of the environment (CREDIT: [969])*

However, the stark increase in active spacecraft will saturate an already congested domain. When these become defunct, they will enlarge the large volume of space debris encircling our planet. Indeed, the overwhelming number of objects in LEO makes it increasingly difficult to find a clear path for rockets to launch new satellites [1008] or to conduct astronomy activities [1009]. Moreover, it increases the probability of space debris collision [969], or the Kessler Syndrome [1010] where the risk of collision is so high that most near earth space activities stop. According to a recent report by the European Space Agency [969], the amount of space debris objects in Low Earth Orbit is likely to increase exponentially even if there were no further space launches in the future (See Figure J.5).

Overall, we expect that these developments will increase the demand for **In-Orbit Servicing (IOS)** platforms and more advanced Space Traffic Management systems [1011]. IOS has been present since the beginning of the space race [1012, 1013], and it refers to on-orbit activities conducted by a space vehicle that performs up-close inspection of or results in intentional and beneficial changes to another resident space object (RSO)[1014]. Among its many uses, we can encounter [1014]. (1) *Non contact support*; (2) *Orbit modification and maintenance*; (3) *Refuelling and commodities replenishment*; (4) *Upgrade*; (5) *Repair*; (6) *Assembly*; and (7) *Debris mitigation*.

Currently, there are plans to launch debris mitigation [1015] vehicles and permanent satellite robot fleets [1016], which will be used to extend the operational life cycle of ageing satellites in LEO and GEO orbits [42]. Some companies are already envisioning the deployment of on-orbit fuel deposits, which will allow them to act as on-demand service stations [1017]. R&D on robotic arms for manufacturing or fluid transfer systems designed for operation in microgravity [1018] will be key for IOS-wide implementation [1012].

Communications

In 1970, with only three space-capable nations on Earth, NATO started a programme that would last until 2005, owning and operating communications satellites to support the Alliance [1019]. Nowadays, certain low probability of detection (LPD), low probability of interception (LPI), and interoperable wireless communications are essential for military tactical and strategic operations. However, the radio frequency (RF) spectrum, whether used for line-of-sight or satellite communications, is highly detectible, congested, contested [1020], and managed by each nation's frequency management directorate. The solution to the RF-associated problems is to move outside the RF spectrum, namely the infrared and visible light portions, through technologies such as Free Space Optical Communications (FSOC) [1021]. Ongoing R&D projects on FSOC (e.g. Laser Communications Relay Demonstration [1022]) are looking into overcoming the limitations of this technology which, unlike RF communications, can't penetrate cloud coverage. At the same time, using quantum technology for data transmissions could improve the speed and security of satellite-to-ground and satellite-to-satellite communications [1023]. Moreover, quantum entanglement through FSOC or Quantum Key Distribution (QKD) networks could potentially prevent the interception of sensitive data, such as those used for orbital manoeuvring or in military communications for the warfighter. However, quantum technologies still need to overcome some limitations, such as infrastructure costs or data validation [1024].

Sensors

Satellites flying in low-earth or remaining in geostationary orbits are used for communication, command and control, navigation, and ISR and are an important asset for supporting military operations. Such Space-Based Systems are made up of sensors that provide information sufficient for determining positional changes (e.g. where the spacecraft is pointed, how fast it is turning, how its speed is changing, etc.), the detection of remote objects in the distance [1025], or the monitorization of local and remote environments [1026]. Several nations like the United States [1027] have started efforts to launch and maintain constellations of Space-based Space Surveillance satellites that will provide timely SSA to meet future space control operations.

Figure J.6: *Space Radar Image of Dnieper River, Ukraine (CREDIT: NASA)*

At the same time, the war in Ukraine has increased the demand for satellite imagery services [1028]. Moreover, it has been shown that open-source information is increasingly considered a valuable source for gathering intelligence. In the satellite domain, an example of open-source intelligence is given by the ESA Copernicus program, which produces vast amounts of free Sentinel data. In addition, high-resolution SAR data (1-3 m) is commercially available through companies such as the

Finnish ICEYE, the first organization to successfully launch Synthetic-Aperture Radar (SAR) satellites with a launch mass under 100 kg [1029].

Currently, there is ongoing research on SAR application [1030] on the fields of automated object recognition [1031]; distributed radar image formation [1032]; and digital signal processing [1033]. In addition, new systems will benefit from ongoing R&D on compressive sensing (CS) [1034], allowing using smaller, cheaper, and lower bandwidth components to obtain high-quality, high-resolution wide field-of-view imagery. Also, the development of Quantum sensors will allow ultra-precise measurements, resulting in sensor performance orders of magnitude better than classical sensors [880].

There are many applications for which increased sensitivity or resolution will significantly benefit the military. Many of the improvements rely on precision timing. Briefly, sensor improvements could be anticipated as follows: (1) *Gravity measurement*; (2) *Rotation sensors*; (3) *Quantum enhanced imaging*; (4) *Quantum dots*; (5) *Magnetic, electric and electromagnetic sensors*; (6) *Quantum computers*;

However, the increased amounts of available sparse data will also require the development of automatic procedures for handling it.

Counter Space (Offensive, Defensive & Resilience)

Space platforms are vulnerable to a wide array of threats [978, 1035], including space weather events, cyber-attacks and jamming, and direct-ascent anti-satellite (ASAT) systems. While some systems incorporate redundancies and protections against different types of threats, all are vulnerable in certain ways to various external factors [1036]. In addition, many satellite systems incorporate a high degree of protection against man-made threats, including jamming, spoofing, and other forms of electronic attack. Still, these satellites remain vulnerable to kinetic attack and space environmental effects.

Counter-satellite, cyber, electromagnetic, and physical attack vectors are evolving [1037, 1038, 1039, 1020]. Resilience requires various measures, including cyber-EM-physical hardening, new operational concepts, and hybrid approaches to space-based platforms as the reliance on space-based assets becomes a potential vulnerability. At the same time, Space Capabilities will have to adapt to the challenges posed by climate change [1040] or space weather. The current applications of commercial space communication networks (e.g. Starlink, OneWeb, etc.) will increase strategic resilience by allowing to overcome possible RED network disruptions (see figure J.4).

Military Implications

Article 1 of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (1966) (RES 2222 (XXI), also known as the Outer Space Treaty [980], holds that *The exploration and use of outer space shall be the common province of all mankind.* One hundred and four countries are signatories to this treaty. Thus, under International Law, outer space exploration is only conducted for peaceful purposes. However, the document was signed over 50 years ago, and as the rush to space gains new momentum, its limitations, especially as it applies to commercial exploitation, are becoming apparent [1041].

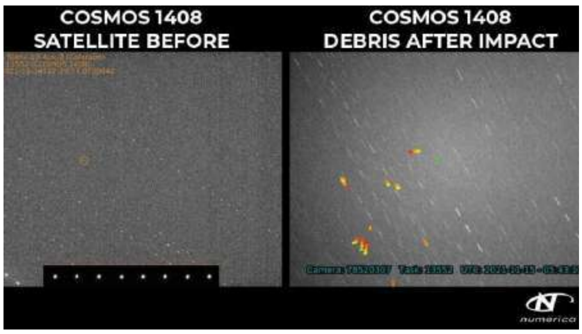


Figure J.7: *Russian ASAT test on Nov. 15 2021 (CREDIT: [978])*

In reality, space has been a contested domain for many years [1042]. The United States [1043], Russia [1043], China [1044], and India [1045, 1046] have successfully tested anti-satellite (ASAT) weapons and some other emerging space nations are proving cable of developing other counter space capabilities [978]. Just between 2021 and 2022 alone, five major events are worth being highlighted [978]:

1. The launch and behaviour of a new Chinese GEO Satellite, SJ-21;

2. The July launch of a hypersonic gliding vehicle;
3. The November 2021 Russian direct-ascent ASAT test in LEO (See J.7);
4. Russia's GPS jamming in Ukraine; and
5. The August 2022 launch of KOSMOS-2558 a Russian inspector satellite [1047].

These physical threats are in addition to the urgency of securing satellites from cyber-attacks [1048] from hijacking [1049]. Indeed, some of today's satellites are as vulnerable as the Internet of Things (IoT) devices ten years ago [1050]. At the same time, other threats, such as using direct energy weapons (DEW) to blind satellite systems [1051, 1052] or more traditional jamming of satellite communication and control, are still ongoing threats. The latter has allegedly been used in the conflict in Ukraine [978].

BLUE

Continuous and secure access to space services, products and capabilities is essential for the credibility of the Alliance's posture, management of that posture, and the conduct of the Alliance's operations, mission and other activities. NATO requires space systems in the following operational areas:

Enable

Space is a key enabler for military operations. Space services form the foundation of NATO's ability to navigate, track blue and red forces, share intelligence, communicate securely with partners, detect missile launches, and ensure effective command and control. BLUE heavily depends on *Global Navigation Satellite Systems (GNSS)* to support various activities, from precision strikes, tracking of forces or search and rescue missions to support critical infrastructure. However, frequencies are a scarce resource [1053], and these systems are subject to diverse intentional threats such as jamming or spoofing [978]; but also to other unintentional events such as solar storms, RF interference, signal reflection or user error [1054]. In 2017, the UK assessed that a 5-day loss of GNSS services would have a 5.2 Billion USD impact on its economy [1055]). For this purpose, BLUE needs to develop alternative systems such as quantum PNT systems [1056] and other technologies to overcome possible disruptions[1057] on operations caused by a GNSS denied environment. Finally, BLUE forces will also rely on more advanced Deep-Space Positioning Systems (DPS) with the extension of BLUE operations beyond cislunar reach.

Prepare

As the ultimate high ground, space provides the necessary perspective on physical operating domains. Space-based sensors support the intelligence preparation of the battlespace or operational environment.

Project

Space is key to establishing, preparing and sustaining sufficient and effective presence at the right time, including building up forces through appropriate and graduated readiness, meeting requirements, and keeping the flexibility necessary to adapt to possible changes in the strategic environment.

Figure J.8: *L3Harris Counter Communications System (CCS) (CREDIT: [1058])*

A key benefit of space access is that it increases BLUE's ability to respond, thus making it crucial for deterrence [1035], which is largely based upon the adversary knowing that its adversary is prepared to act [1059]. Today, BLUE uses smallsats of different sizes and degrees of autonomy to support many additional military capabilities as they can perform military missions that once were reserved for large spacecraft. In addition, increased use of smallsats with new low-powered passive and active sensors will increase situational awareness around the planet and raise space situational awareness. At the same time, smallsats can be used for proximity and rendezvous operations. In the future, swarms, increased autonomy and large constellations will further improve C4ISR capabilities, taking advantage of short revisit times, rapid launch and flexible positioning.

Engage

BLUE has demonstrated that it can deny RED from accessing space and deceive, disrupt, deny, degrade or destroy RED assets in space [1043, 978]. In addition, maintaining the technological edge will give BLUE a great advantage over RED (e.g. development of unique Counter Communication Systems. See: J.8[1058]).

Protect

Space Based Infrared Systems (SBIRS) allow the detection of unusual heat signals [1060]. An advantage of such an approach will be the possibility of complete Tactical Ballistic Missile (TBM) and hypersonic launch detection and tracking. This capability would further support deploying strategic headquarters (both for the NATO Force Structure and at a national level) and forces and capabilities to support any Alliance mission. These also include the capability to contribute to deterrence. *Space Situational Awareness (SSA)* is required to understand the operational environment [163], which enhances BLUE's strategic anticipation and resilience. This capability includes detecting, identifying, and tracking objects in space and understanding the effects of space weather. BLUE's approach to SSA must evolve to meet the challenge of detecting small space targets in a contested domain. For this purpose, BLUE will need to have the ability to handle large volumes of data coming from different sources [163]. Space Surveillance and Tracking (SST) represents a key element in this scenario, which ensures that Resident Space Objects (RSOs) are continuously detected and tracked. BLUE R&D on RSO localization (e.g. GPS-based active transmitters [1061] will ensure that collision avoidance is performed effectively with minimum risk of loss of system functionality.

Sustain

Nowadays, BLUE is advancing the development of Rapid and Reusable launch systems, which will facilitate Space Mobility and logistics by reducing the cost of access to space and allowing quicker operational turnarounds. In the future, BLUE will benefit from multiple satellite constellations that will provide timely support to forces and be more frequently refreshed and updated. At the same time, BLUE On-Orbit Servicing (OOS) capabilities will be crucial to sustaining critical systems at risk due to collisions with space debris, space weather, or RED activity [1062, 1012]. Finally, BLUE will benefit from developing space transportation technologies as a new mode of point-to-point global terrestrial delivery of equipment and personnel, as an alternative and complement to traditional air, land and surface modes for global supply chain [1063].

Inform

Figure J.9: *Near Belgorod, Feb. 2022, SAR image of Russian military vehicles (CREDIT: Capella Space / Middlebury Institute of International Studies).*

The development of new space-oriented technology and techniques with enhanced sensitivity and imaging capability for future Intelligence, Surveillance and Reconnaissance (ISR) missions is a requirement. Such new capabilities will be essential over the next 20 years to maintain situational awareness and support BLUE force planning and decision-making, especially in areas where data can't be obtained from other domains [1062]. Satellite imagery has been a crucial enabler of Ukrainian forces and NATO situational awareness during the Russian invasion of Ukraine. Open Source Intelligence (OSINT) from commercial Earth Observation satellites has empowered

Ukraine's war effort [1064]. New **sensors** offer BLUE great potential for space-based imaging as space-borne systems are unaffected by atmospheric attenuation. The development of specialised electro-optic/infrared (EO/IR) sensors notably to support missile defence [1065], SAR (synthetic aperture radar), Electronic Intelligence (ELINT) (e.g. Automated Identification System (AIS) [1031]) continues. At the same time, improved procedures and techniques for camouflage [1066], deception and jamming are needed to enable covert ISR gathering of RED forces in the target area. At the same time, the increase in detection ranges for ground base Passive Coherent Location (PCL) radars significantly increases capability. Such PCL radars, augmented by space-based receivers [1067], will potentially allow a real-time RAP (Recognized Air Picture) over a much wider area RED or neutral territory. It will enable an in-depth view of activity over a wide area and provide detection, precise tracking and identification of targets using adversary or neutral nation transmitters of opportunity.

C3

Timely access to relevant information is a key success factor for BLUE military operations. Communications and observation (e.g. C4ISR) have always been important motivators for the use of space. These capabilities improve the commanders' capacity to exercise authority over and direct the full spectrum of assigned and attached forces. *Satellite Communications (SATCOM)* are a key component of military operations [1019]. Satellite to Satellite, Satellite to Ground and Satellite to aircraft Free Space Optical Communication (FSOC) [1068, 1021] and Optical Wireless Systems (e.g. Light Fidelity [1069]), will allow BLUE communications to move beyond the Radio Frequency (RF) electromagnetic spectrum. These developments will secure a low probability of detection (LPD), low probability of interception (LPI), and interoperable wireless communications capability. Further, research on quantum communication technologies, such as Quantum Key Distribution (QKD) and the quantum internet, will also enhance BLUE communication services, significantly improving secure communications.

RED

Peer or near competitors will leverage the same advantages as BLUE. There is evidence that RED is developing counter-space and anti-satellite systems (See: J.10) [975, 1043]. Potential threats are pursuing the development of a wide range of capabilities from non-kinetic (such as dazzling, blinding and jamming of space assets) to destructive kinetic systems (such as direct-ascent anti-satellite missiles, on-orbit anti-satellite systems, and laser and electromagnetic capabilities) [978]. The susceptibility of space further exacerbates such space destruction, disruption, degradation and denial capabilities to hybrid approaches and the associated difficulty of attributing harmful effects to space systems [967]. Some threats, such as signal jamming and cyber-attacks, can also be caused by non-state actors, including terrorist organizations. Many threats to Allies' space systems originate in the cyber domain and are likely to increase. In addition to man-made risks, space systems are vulnerable to natural hazards and accidents.

More specifically, the capabilities being developed by potential adversaries could be used against the Alliance, too, among other things:

- Hold space assets at risk, complicating BLUE'S ability to take decisive action in a crisis or conflict.
- Deny or degrade BLUE's space-based capabilities critical to battlespace management, situational awareness, and the ability to operate effectively in a crisis or conflict.
- Create impacts on BLUE's space systems that are damaging or disruptive to economic or public life and violate the principle of free use of space yet fall below the thresholds of the threat of force, use of force, armed attack or aggression.

Interoperability

Interoperability helps all the pieces fit together and run smoothly. NATO has been striving to improve the ability of NATO forces to work together since the Alliance was founded in 1949. Recognizing space as the fifth operational domain will demand increased effort to ensure this. NATO's decision to fully rely on

	LEO Direct Ascent	MEO/GEO Direct Ascent	LEO Co-Orbital	MEO/GEO Co-Orbital	Directed Energy	Electronic Warfare	Space Situational Awareness
United States	x	-	x	x	x	x	x
Russia	x	x	x	x	x	x	x
China	x	x	x	x	x	x	x
India	x	-	-	-	x	x	x
Australia	-	-	-	-	x	x	x
France	-	-	-	-	x	x	x
Iran	-	-	-	-	-	x	x
Japan	-	-	-	-	x	x	x
North Korea	-	-	-	-	-	x	x
South Korea	-	-	-	-	x	x	x
United Kingdom	-	-	-	-	-	x	x

Figure J.10: *Counter Space Capabilities (CREDIT: [975])*

Ally-owned assets shouldn't limit the Alliance's actions in space. Interoperability does not necessarily require common military equipment. What is important is that equipment can share common facilities and interact, connect and communicate, and exchange data and services with other equipment.

It is important to acknowledge that interoperability issues may arise around access to highly classified space-derived information, operational use of commercial communication networks, sharing of exploitation results, policies on using data collected by commercial sensors, and procedures for the Alliance to request collection on targets by national means. Interoperability solutions will require that NATO continues to provide a forum to share information and supports missions and operations with space-based systems. Common interests and a willingness to work together are characteristic of international activities in space, including those involving NATO. Such coordination and collaboration will be essential to ensure interoperability and the long-term utility of space to NATO's success.

S&T Development

State of Development

This section addresses the state and rate of development of science in space. Further, it answers the question: What does space mean for developing related scientific areas, or what synergistic relationship does it have with these NATO S&T Priorities?

AI

The commercial and military utility of small-sats [1003] has expanded dramatically. Nevertheless, research efforts are expanding to reduce further the size, weight, power, and costs (SWaP-C) and expand the possible capability, effectiveness, and types of sensor payloads [153]. Increased autonomy and embedded AI improve collection management, onboard processing and fusion, and inter-satellite coordination. Actively collaborating satellites (constellations) will increase operational effectiveness.

Data

Vast quantities of sensor data will support a more comprehensive understanding and approach to the operational environment. Combined with AI, this will enable a more holistic approach to operational planning. However, national adoption of critical BDAA technologies (e.g. 5G) may create a significant digital divide due to differing threat perceptions and adoption of underlying technologies. A lack of standards and the development of incompatible or *untrustworthy* systems may limit NATO's ability to share space-derived data and other sensitive data.

RAS

The increased use of space and mega-constellation development will benefit from ongoing developments in Robotics and Autonomous Systems (RAS) for In-orbit satellite servicing (IOS). IOS demonstration projects have already been successful or are planned for the near term [1070] [1071] [1014]. Such capabilities will profoundly affect space access. In addition, these technologies, with only a change in intent, offer potential new anti-satellite capabilities. At the same time, RAS in space enables human exploration and habitation in near and deep space. Furthermore, space agencies and commercial companies are researching advanced robotic technologies to de-orbit non-functional and large objects.

Hypersonics

Countering HCM & HGV will require improved terrestrial and space-based sensors for detection, identification and tracking, as well as enhanced navigation and control to ensure successful intercepts. In addition, integrated data fusion and autonomous functions will need to be improved to support the short decision times available.

Quantum

Integrating quantum technologies in the space domain will improve existing capabilities and allow for developing cislunar and deep space operations. For example, quantum navigation will enable space platforms to navigate without relying on GNSS systems using the local gravitational environment; quantum sensors will obtain better measurements; quantum key distribution networks will allow decision-makers to maintain more secure communications.

Materials

Additive manufacturing (AM), or 3D printing as it is also known, creates three-dimensional solid objects of virtually unlimited shape from digital models and a wide variety of metals, plastics and resins [847]. Reduced costs using these technologies will also enable increased availability, agile reconfiguration of constellations and reliability. They will also significantly reduce the cost of entry and improve access to such systems by state, non-state or hyper-empowered groups. At the same time, novel materials (e.g. graphene) will enable new capabilities for space operations.

Energy

Operations in cislunar space require significant improvements to propulsion technologies beyond chemical (low efficiency but high thrust) and electric (high efficiency but low thrust) methods for generating thrust. More recent research is focused on on-orbit testing 2025 of nuclear thermal propulsion (NTP) using high-assay and low-enriched uranium [42]. Commercial companies such as SpaceX and RocketLab aspire to meet lower turnaround times. Nevertheless, R&D continues to improve the performance and reliability of such rapid task-tailored systems and incentivize commercial development [42]. In addition, there is a need for scalable, responsive and reusable launch systems designed to launch larger satellites into low-earth and sub-orbital trajectories [42]. Turnaround times on the order of 24 hours are envisaged with sustained operations. Commercial systems for space tourism have already been demonstrated.

E&EM

The development and refinement of space-based laser communications will be key for improved deep space and cislunar operations. In addition, the increase in space systems will require the development of a reconfigurable inter-satellite optical communications terminal such as DARPA's Space-Based Adaptive Communications Node (Space-BACN) program [42] to overcome the challenge of connectivity between constellations.

STO Activities

Several STO Scientific and Technical Committees have produced significant research on space technologies. Currently, the Applied Vehicle Technology (AVT) Panel, the Information Systems Technology (IST) Panel, the NATO Modelling and Simulation Group (NMSG), the Systems Concepts and Integration (SCI) Panel, and the Sensors and Electronics Technology (SET) Panel; have numerous ongoing activities on several topics aligned to these technologies, such as:

- AVT-ST-009: Technical Support to NATO Next Generation Rotorcraft Capability (NGRC)
- IST-189 (COM): Hybrid Military and Commercial SATCOM Networks
- MSG-187: Space Weather Environmental Modelling (SWEM)
- SAS-159: How could Technology Development Transform the Future Operational Environment
- SAS-166: Wargaming Multi-Domain Operations in an A2/AD Environment
- SCI-329: Capabilities for Sensing, Search, and Surveillance in the Arctic
- SCI-346: Space Risk Assessment Matrix (S-RAM)
- SCI-349: Heterogeneous Data-Driven Space Domain Decision Intelligence
- SCI-350: NATO Alliance SmallSat Constellation Effort (LSAT)
- SCI-SAS-351: Alliance Space Deterrence Framework
- SCI-SET-353: C-UAS Mission-Level Modelling & Simulation
- SCI-SET-355: Cross-Panel Collaborative Experimentation for Improved Space Situational Awareness (SSA)
- SET-279: Space-based SAR and Big Data Technologies to support NATO Operations
- SET-293: RF Sensing for Space Situational Awareness
- SET-320: New Frontiers in Modern Passive Radars
- SET-SCI-297: Space Sensors and Space Situational Awareness

Scientometric Analysis

The Science & Technology Ecosystems Analysis Model (STEAM) has analyzed over seven million publications, of which 111,790 are aligned to space technologies. The chart immediately below (see: Figure J.11) provides a brief overview of the most repeated words within the publications aligned to space technologies:

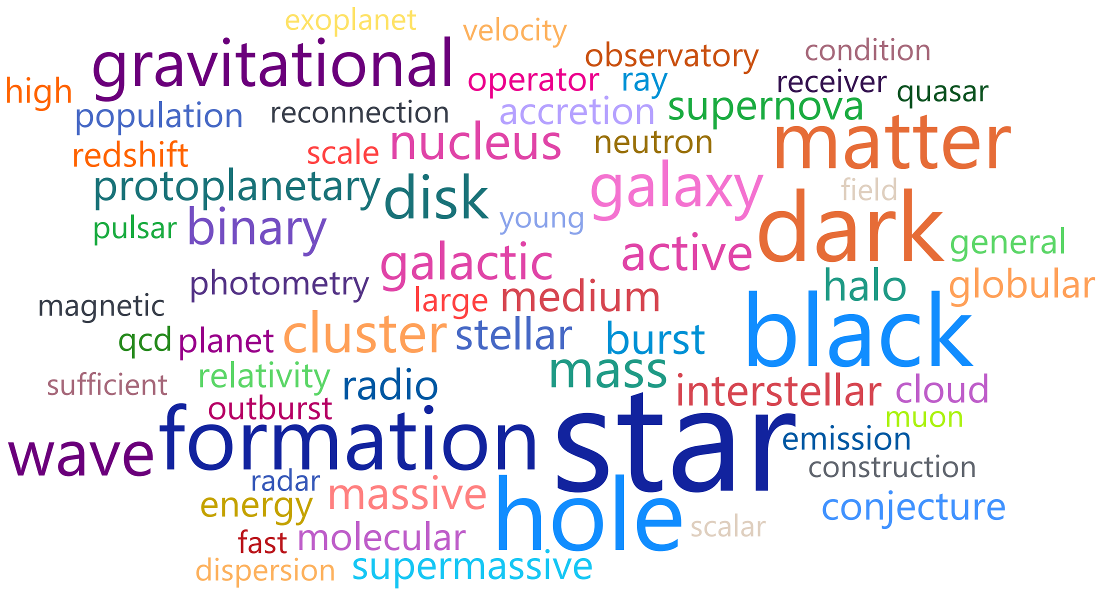


Figure J.11: *STEAM - Space - Keywords*

Survey Results

The following table presents the assessed potential impact, state and rate of development and identifies areas for focused research.

Table J.3: *Space Technologies (ST) 2023 - 2043.*

EDT	Technology Focus Areas	Impact	TRL	Horizon
Space	Communications	High	9	2022-2025
	Counter Space	High	5-6	2030-2035
	Platforms	High	9	2022-2025
	Propulsion & Launch	High	9	2022-2025
	Sensors	High	7-8	2022-2025

Conjecture Card: Space Technologies

A. Star Wars Satellites  Surgically deliver a kinetic or directed energy weapon (DEW) effect from space to targets larger than 10cm in diameter.	**B. On Orbit Repair**  Conduct on-orbit construction, repair, deconstruction or covert/overt modifications of C4ISR satellite systems and constellations.	**C. Solar Space Power**  Deliver large quantities of energy anytime and anywhere on Earth via microwave, provided you have the necessary equipment to receive it.
D. Commercial Space ISR  Use and fuse commercial space-derived data providing global situational awareness of air, space and maritime surface traffic, including detecting dark targets in real-time.	**E. Instant launch**  Launch single-purpose limited life satellites & swarms into low Earth orbit (LEO) from forward-operating bases.	**F. Global Passive Radar**  Space based collection and targeting using GPS or other ambient EM signals.
G. Orbiting Base  Employ persistent counterattacks or observation bases for Earth-orbiting objects, defeating earth-oriented countermeasures.	**H. Weaponized Space Debris**  Plausibly deny the destruction of an adversary's' satellite or ground strike.	**I. Deep insertion**  Strategic resupply and force projection anywhere on Earth in hours.
J. Kessler Syndrome  Space debris has made launch and operations in near Earth orbit a high-risk activity, nearly shutting off access to space entirely.	**K. Space Elevator**  Space elevators greatly reduce the cost of space launch to pennies per Kg.	**L. Resource Ownership**  Commercial mining of asteroids and the moon have created significant conflict (legal and kinetic) and destabilised national economies.

K. STO Technical Network Survey

The results of the subject matter STO experts' survey are summarised below.

Artificial Intelligence

Table K.1: *Artificial Intelligence (AI) 2023 - 2043.*

EDT	Technology Focus Areas	Impact	TRL	Horizon
AI	Advanced AI	Revolutionary	3-4	2035 or (+)
	Applications	High	5-6	2025-2030
	Counter AI	Revolutionary	3-4	2030-2035
	Human-Machine Symbiosis	Revolutionary	3-4	2035 or (+)

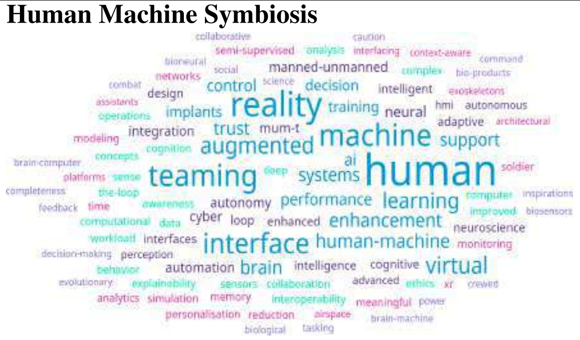
Table K.2: *AI - Keywords*

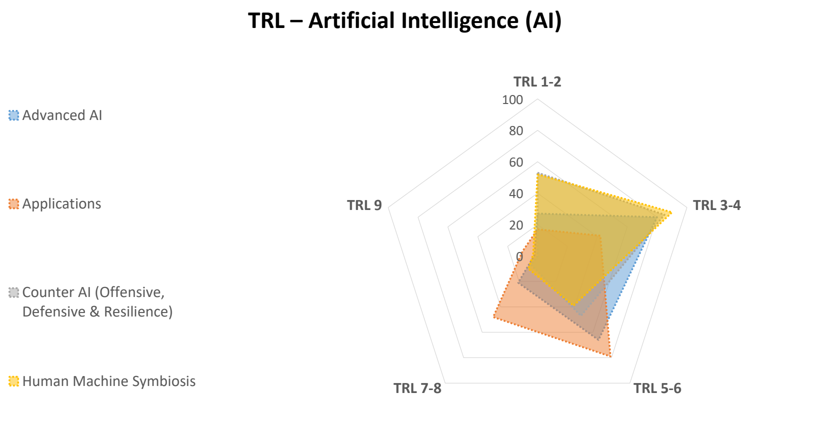
Advanced AI

AI Applications

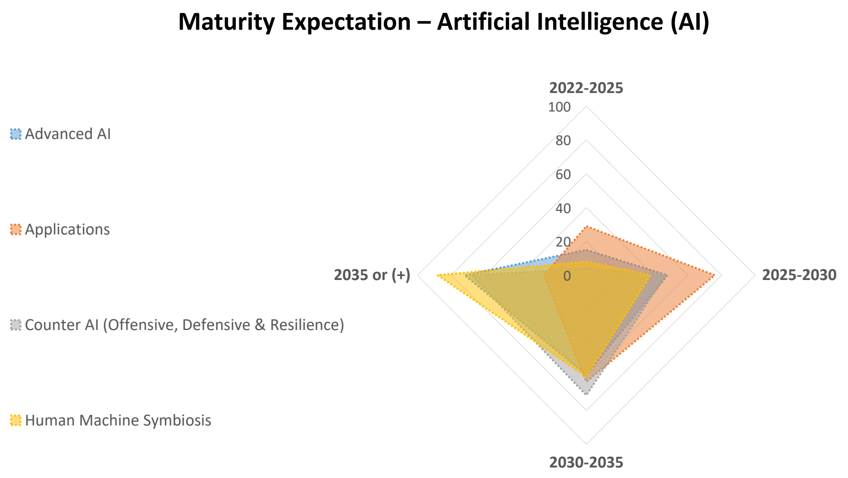
Counter-AI

Human Machine Symbiosis

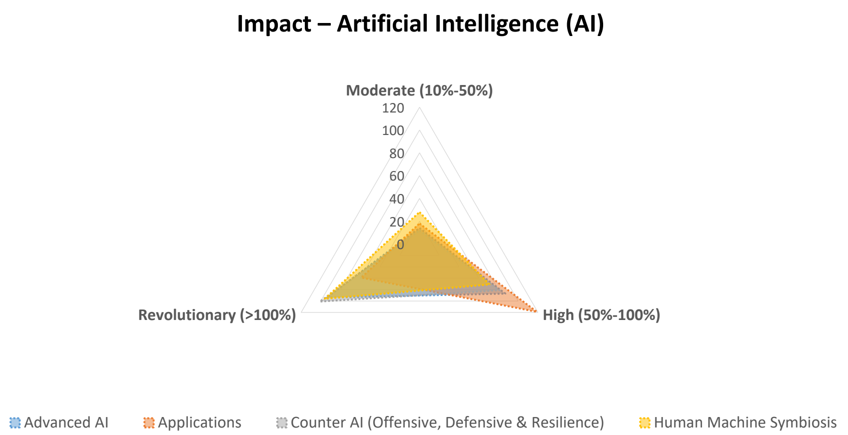




(a) AI - TRL).



(b) AI - Maturity).



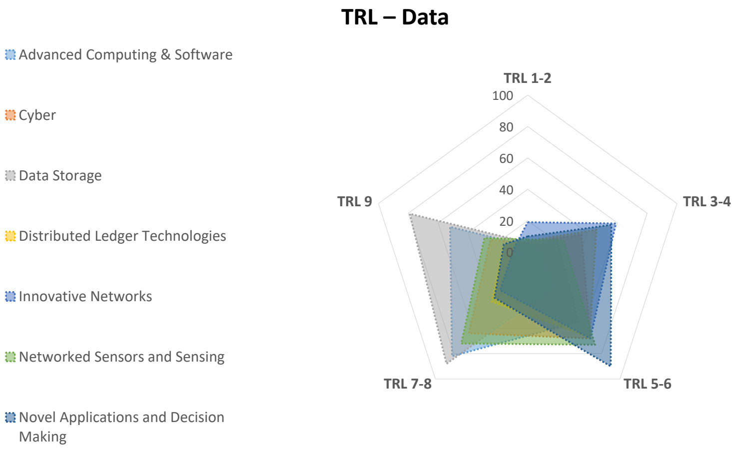
(c) AI - Impact).

Figure K.1: *AI - STO Survey Results*

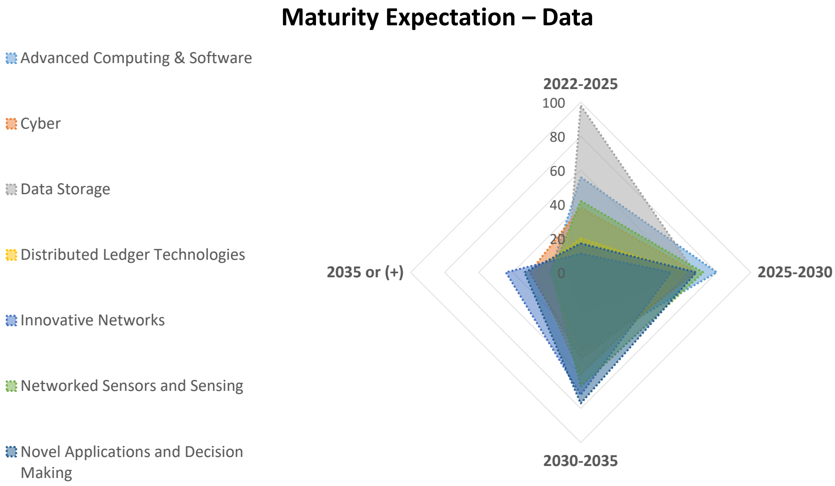
Data

Table K.3: Big Data, Advanced Analytics, and Information Communication Technologies (Data) 2023 - 2043.

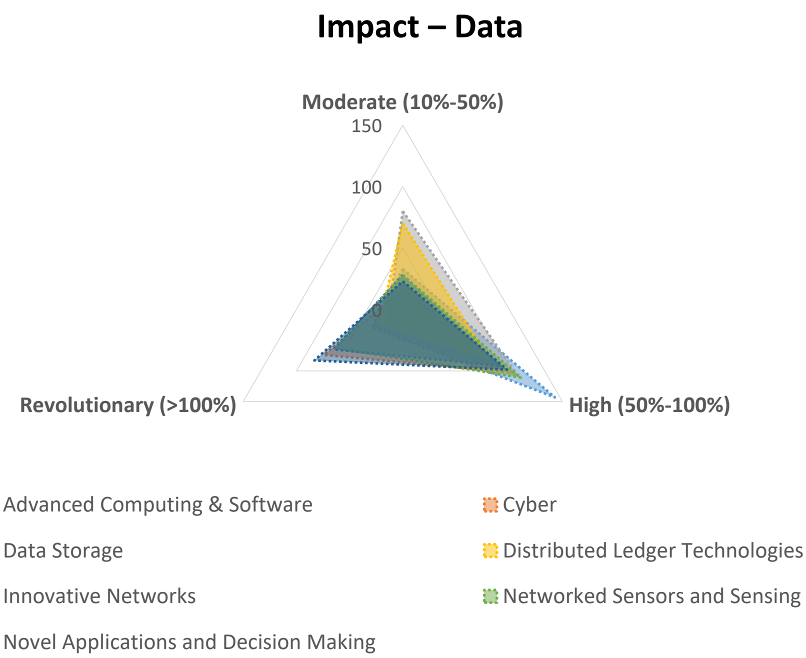
EDT	Technology Focus Areas	Impact	TRL	Horizon
Data	Advanced Computing & Software	High	7-8	2025-2030
	Novel Applications & Decision Making	High	5-6	2030-2035
	Distributed Ledger Technologies	High	5-6	2025-2030
	Innovative Networks	High	5-6	2030-2035
	Networked Sensors & Sensing	High	5-6	2025-2030
	Data Storage	High	7-8	2022-2025
	Cyber	High	5-6	2025-2030



(a) DATA - TRL).



(b) DATA - Maturity).

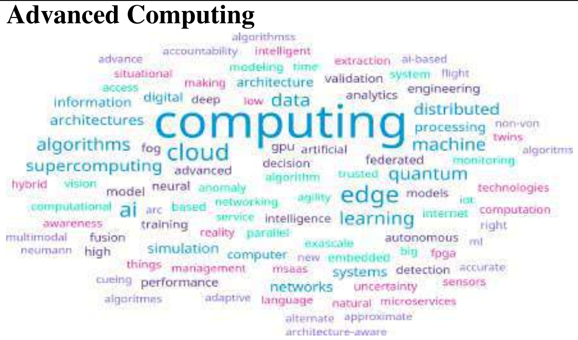


(c) DATA - Impact).

Figure K.2: *DATA - STO Survey Results*

Table K.4: *DATA - Keywords*

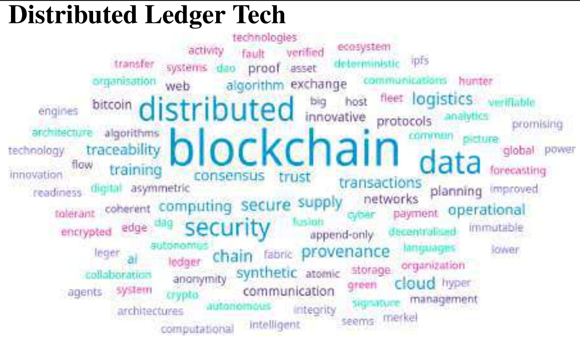
Advanced Computing



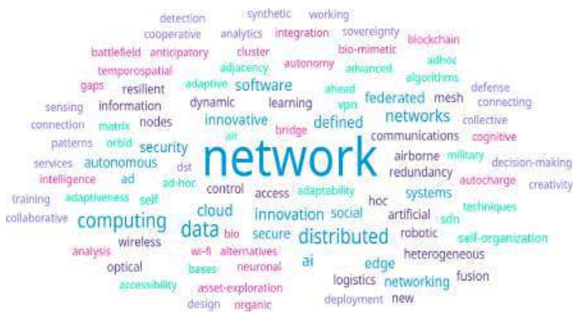
Cyber

Data Storage

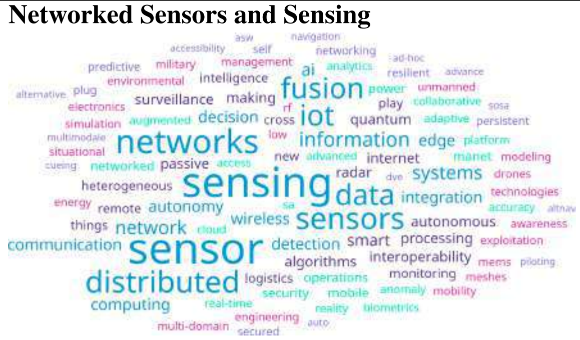
Distributed Ledger Tech



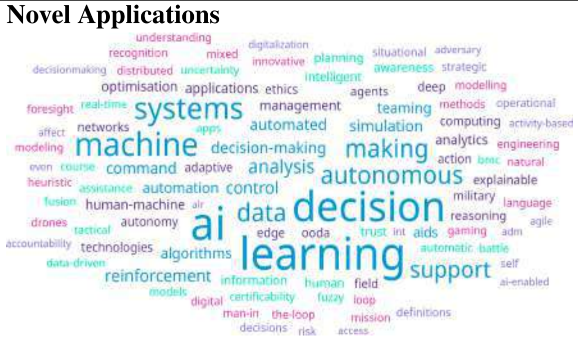
Innovative Networks



Networked Sensors and Sensing



Novel Applications



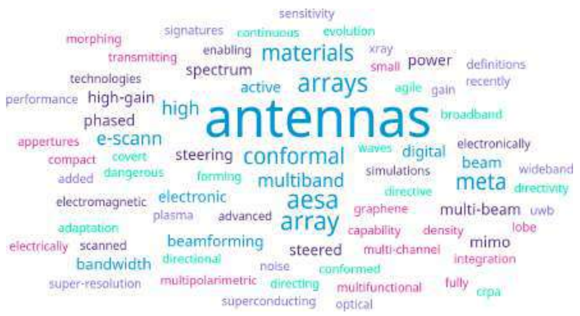
Electronics & Electromagnetics (E&EM)

Table K.5: *Electronics & Electromagnetics (E&EM) 2023 - 2043.*

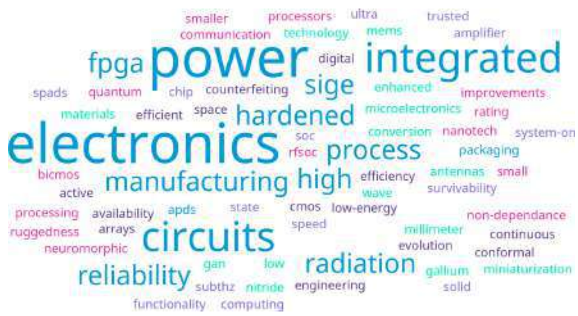
EDT	Technology Focus Areas	Impact	TRL	Horizon
E&EM	Antennas	High	9	2022-2025
	Directed Energy Weapons	High	5-6	2030-2035
	Microelectronics	High	9	2022-2025
	Photonics & Lasers	High	7-8	2025-2030
	Spectrum & Signature Management	High	5-6	2025-2030

Table K.6: *EM - Keywords*

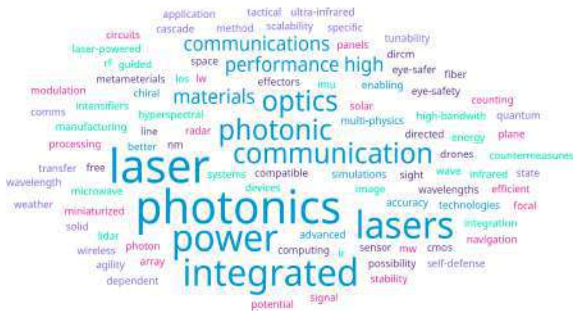
Advanced Antennas



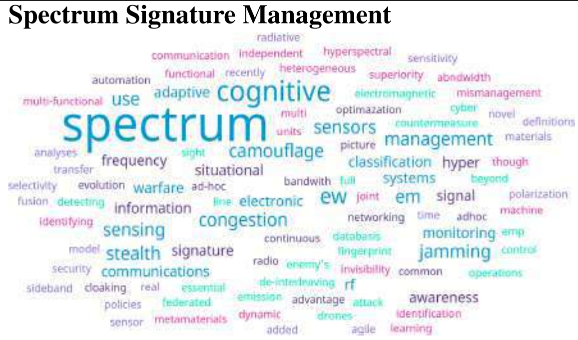
Microelectronics



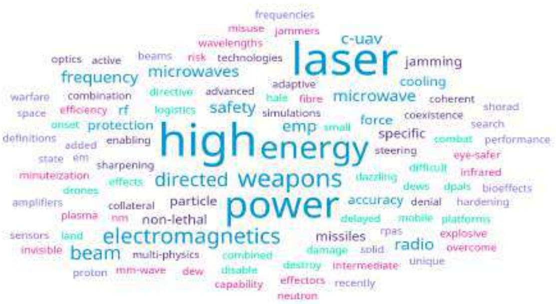
Photonics and Lasers

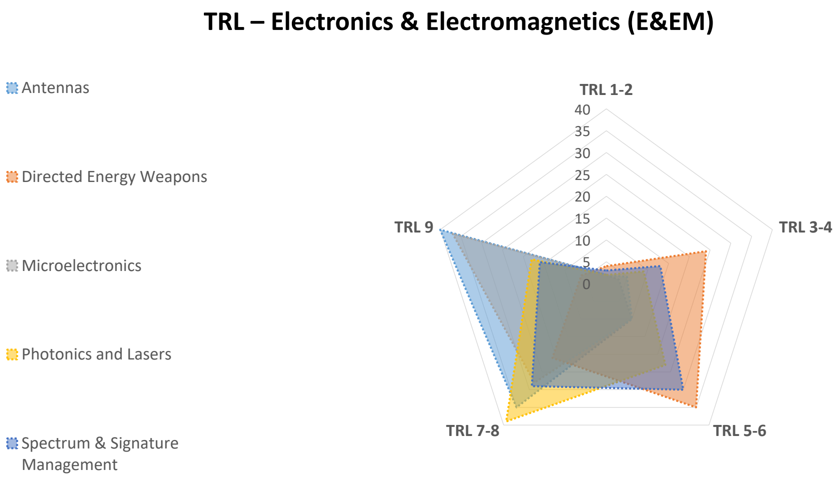


Spectrum Signature Management

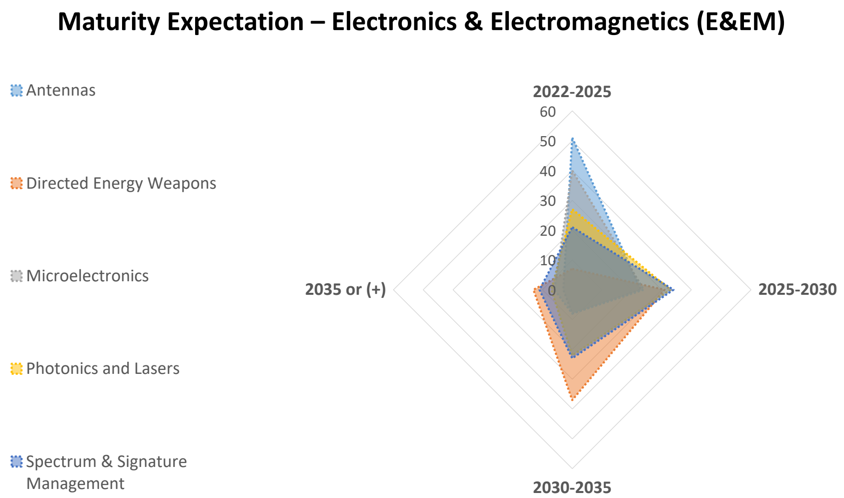


Directed Energy Weapons

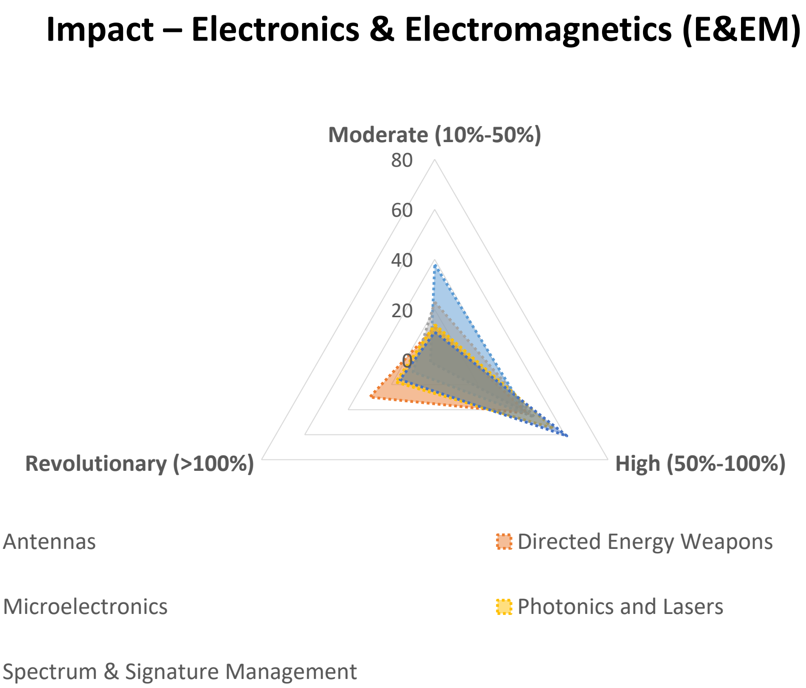




(a) EM - TRL).



(b) EM - Maturity).



(c) EM - Impact).

Figure K.3: *EM - STO Survey Results*

Energy & Propulsion

Table K.7: Energy & Propulsion (Energy) 2023 - 2043.

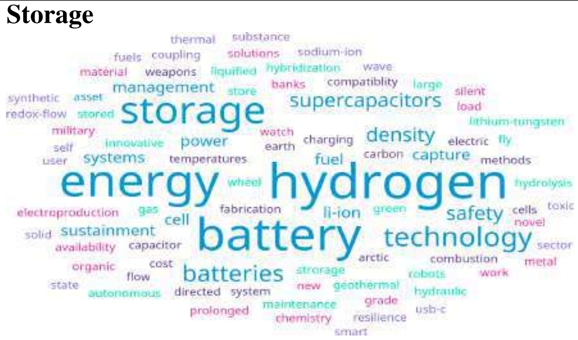
EDT	Technology Focus Areas	Impact	TRL	Horizon
Energy & Propulsion	Energy Generation	High	5-6	2025-2030
	Energy Storage	High	5-6	2030-2035
	Propulsion	High	5-6	2025-2030
	Transmission	High	5-6	2025-2030

Table K.8: ENERGY - Keywords

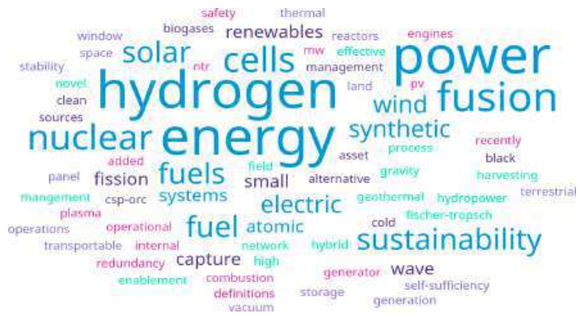
Propulsion

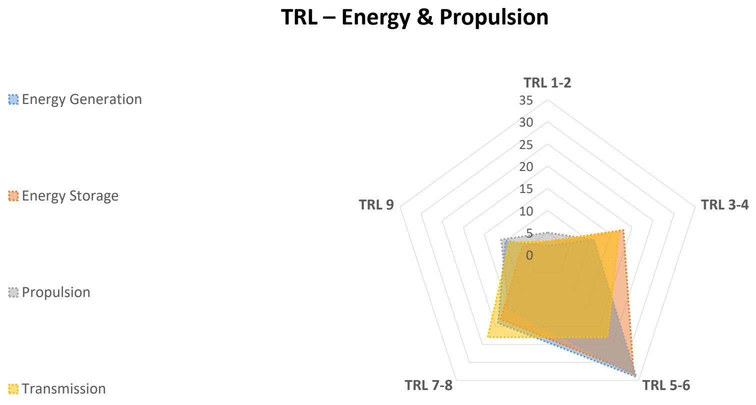
Transmission

Storage

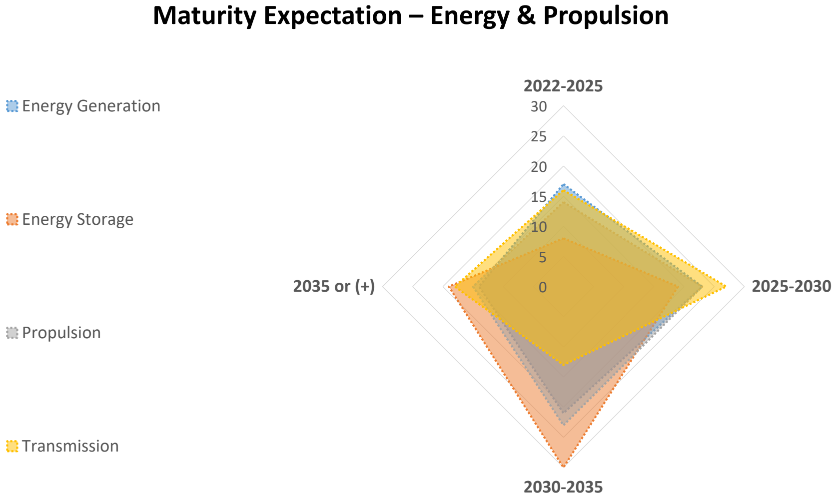


Generation

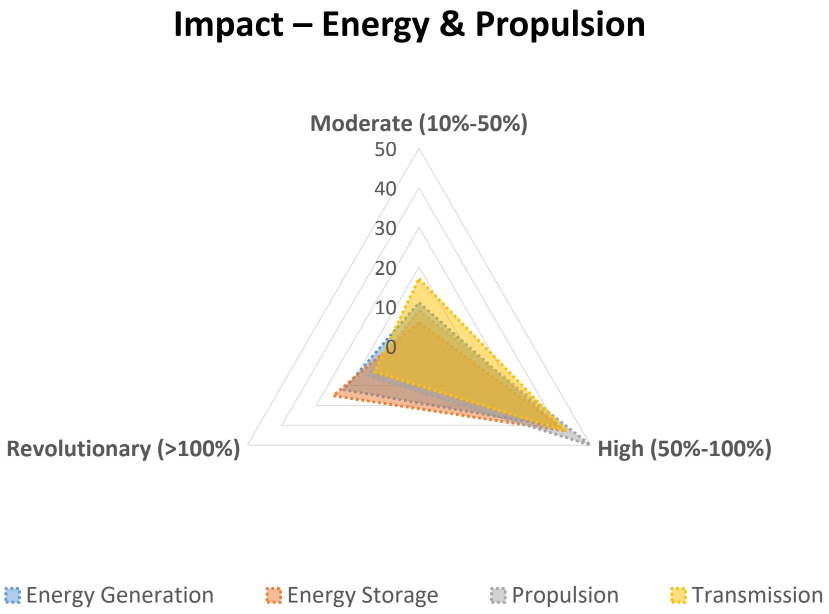




(a) ENERGY - TRL).



(b) ENERGY - Maturity).



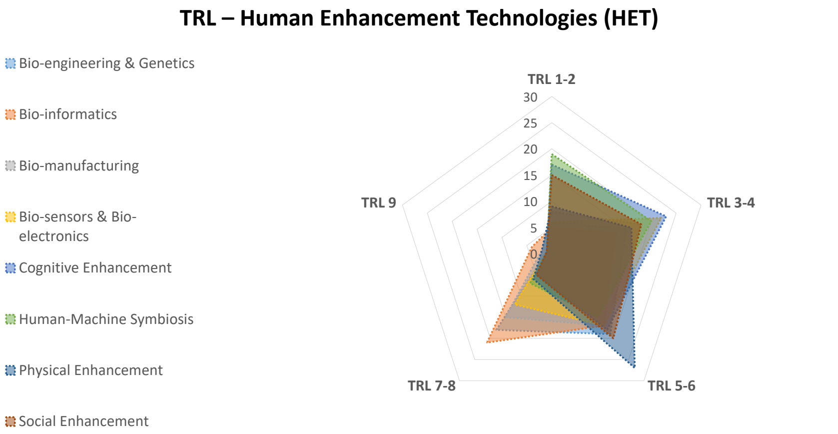
(c) ENERGY - Impact).

Figure K.4: *ENERGY - STO Survey Results*

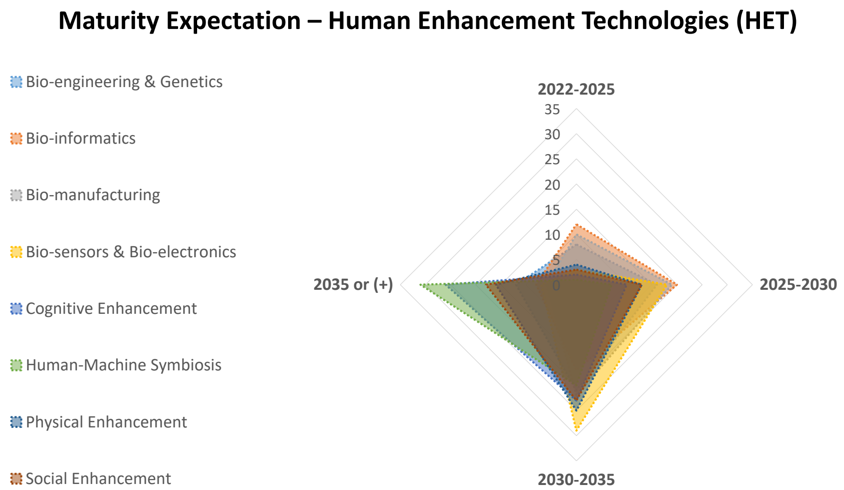
Biological and Human Enhancement Technologies (BHET)

Table K.9: *Biological and Human Enhancement Technologies (BHET) 2023 - 2043.*

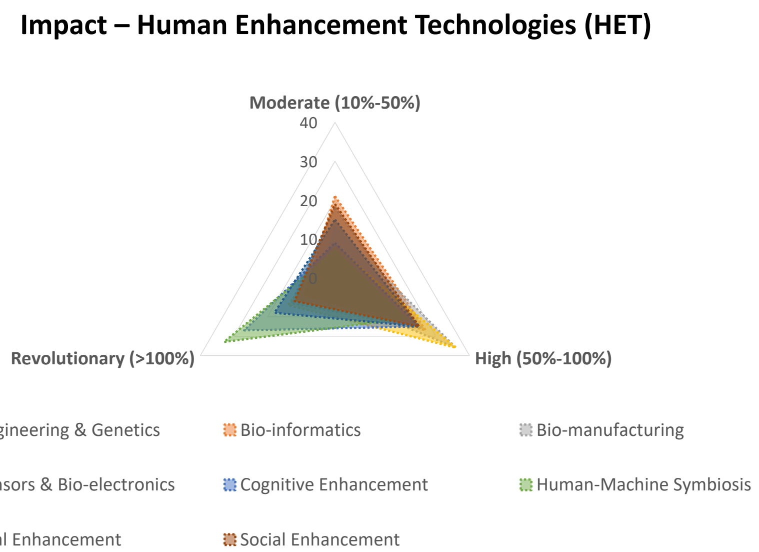
EDT	Technology Focus Areas	Impact	TRL	Horizon
BHET	Bio-engineering & Genetics	High	5-6	2030-2035
	Bio-informatics	High	7-8	2025-2030
	Bio-manufacturing	High	3-4	2030-2035
	Bio-sensors & Bio-electronics	High	3-4	2030-2035
	Cognitive Enhancement	Revolutionary	3-4	2035 or (+)
	Human-Machine Symbiosis	Revolutionary	3-4	2035 or (+)
	Physical Enhancement	High	5-6	2030-2035
	Social Enhancement	High	5-6	2030-2035



(a) BHET - TRL).



(b) BHET - Maturity).

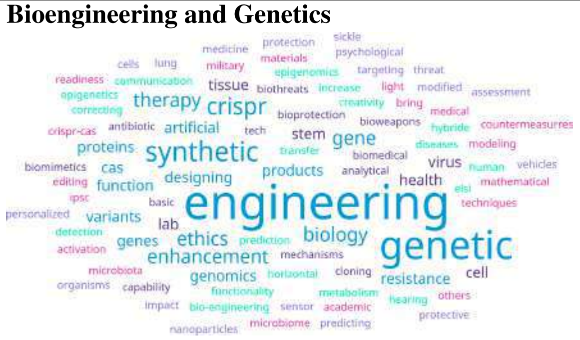


(c) BHET - Impact).

Figure K.5: *BHET - STO Survey Results*

Table K.10: BHET - Keywords

Bioengineering and Genetics

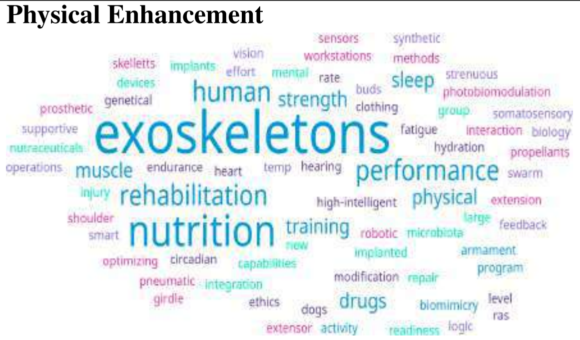


Biomanufacturing

Cognitive Enhancement

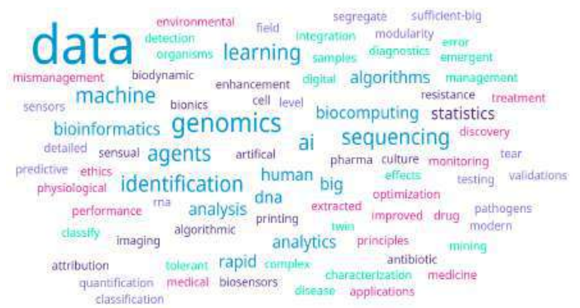
Human-Machine Symbiosis

Physical Enhancement



Social Enhancement

Bioinformatics



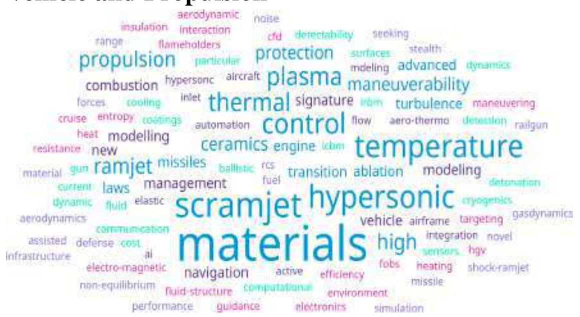
Biosensors and Bio-electronics

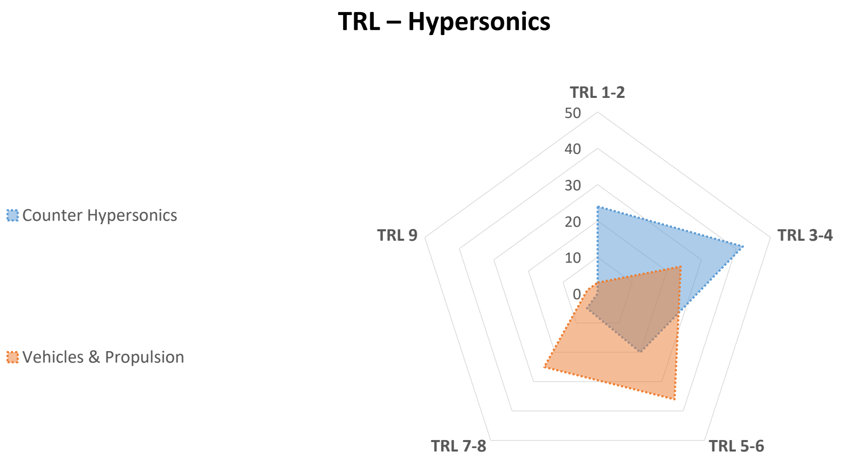
Hypersonics

Table K.11: *Hypersonics 2023 - 2043.*

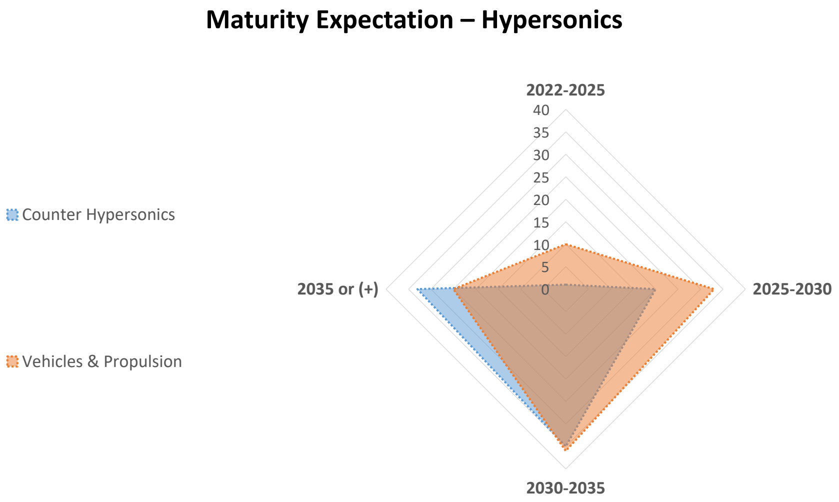
EDT	Technology Focus Areas	Impact	TRL	Horizon
Hypersonics	Counter Hypersonics	High	3-4	2030-2035
	Vehicles & Propulsion	High	5-6	2030-2035

Table K.12: *HYPERSONC - Keywords*

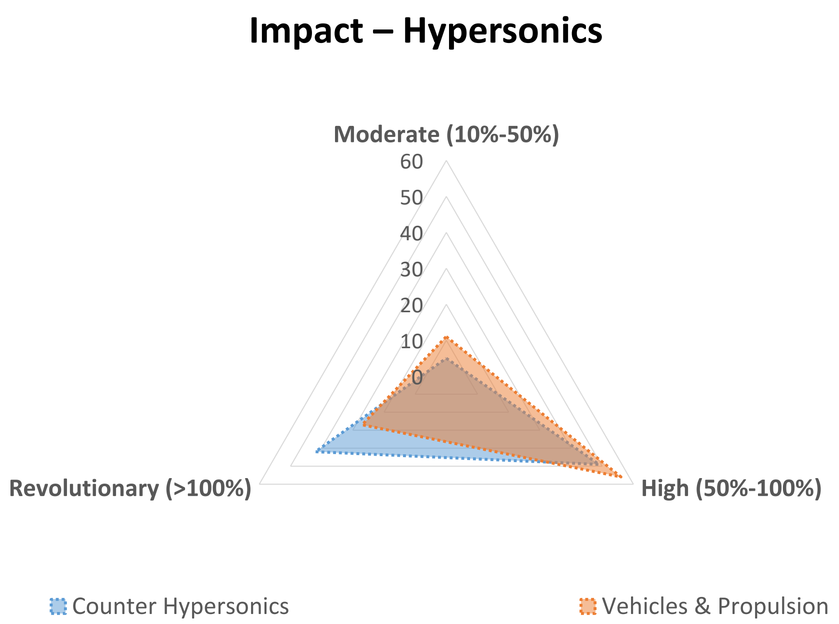
Vehicle and Propulsion	Counter Hypersonics
	



(a) Hyper - TRL).



(b) Hyper - Maturity).



(c) Hyper - Impact).

Figure K.6: *Hypersonic Technologies - STO Survey Results*

Materials

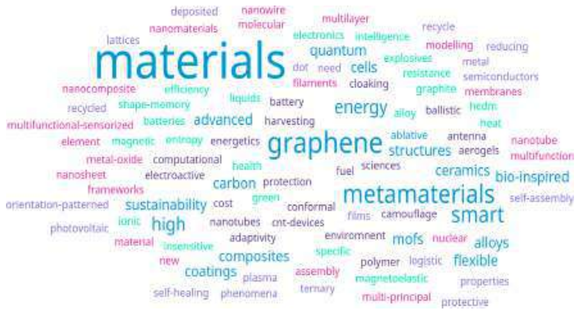
Table K.13: Novel Materials and Advanced Manufacturing (Materials) 2023 - 2043.

EDT	Technology Focus Areas	Impact	TRL	Horizon
Materials	Nano-materials & Nano-manufacturing	High	5-6	2025-2030
	Novel Design & Additive Manufacturing	High	5-6	2025-2030
	Novel Materials	High	3-4	2030-2035

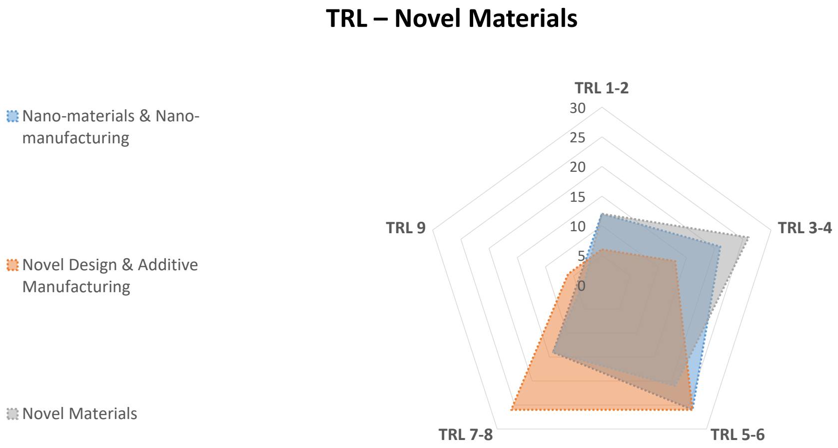
Table K.14: MATERIAL - Keywords

Nano-Materials and Manufacturing

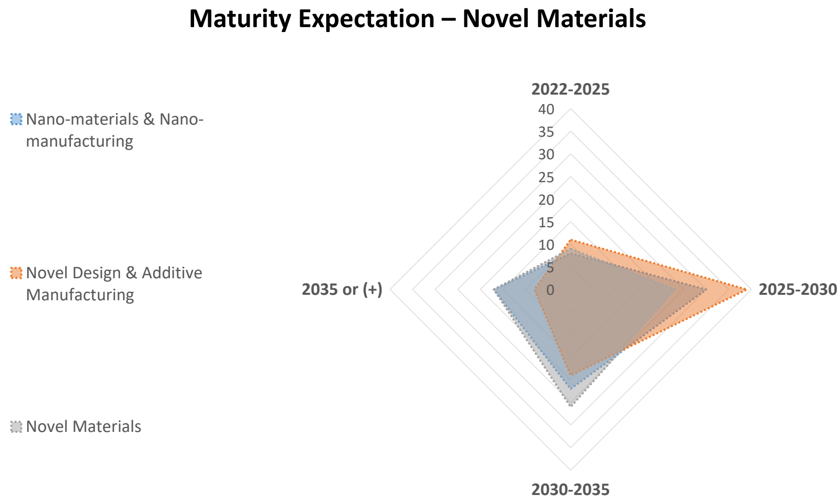
Novel Materials



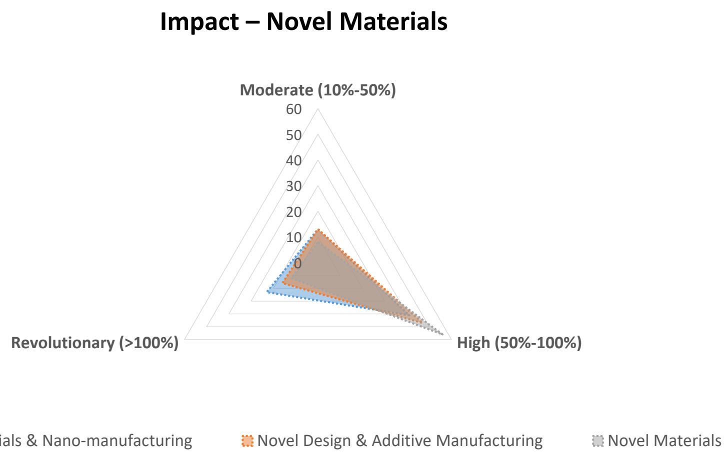
Novel Design and Additive Manufacturing



(a) MATERIAL - TRL).



(b) MATERIAL - Maturity).



(c) MATERIAL - Impact).

Figure K.7: *MATERIAL - STO Survey Results*

Quantum

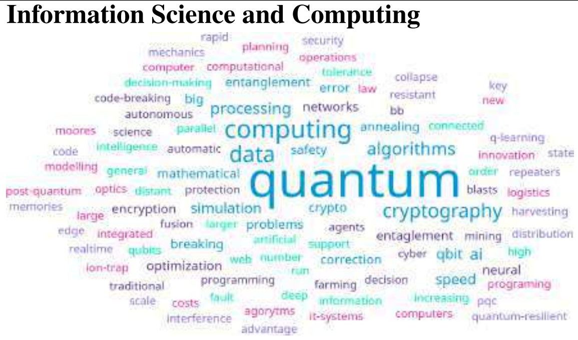
Table K.15: Quantum Technologies (QT) 2023 - 2043.

EDT	Technology Focus Areas	Impact	TRL	Horizon
Quantum	Communications	High	3-4	2030-2035
	Information Science & Computing	High	3-4	2035 or (+)
	Sensors	High	3-4	2035 or (+)

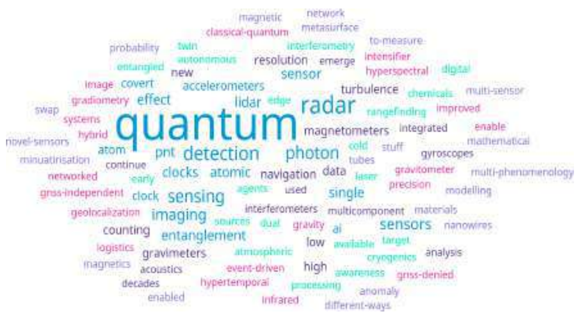
Table K.16: QUANTUM - Keywords

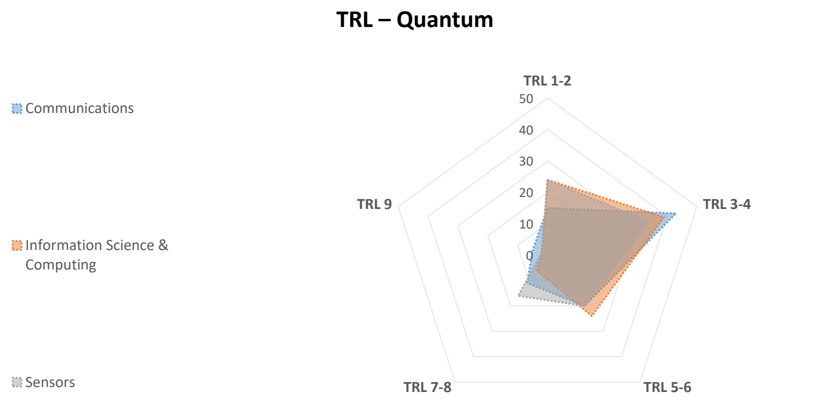
Communications

Information Science and Computing

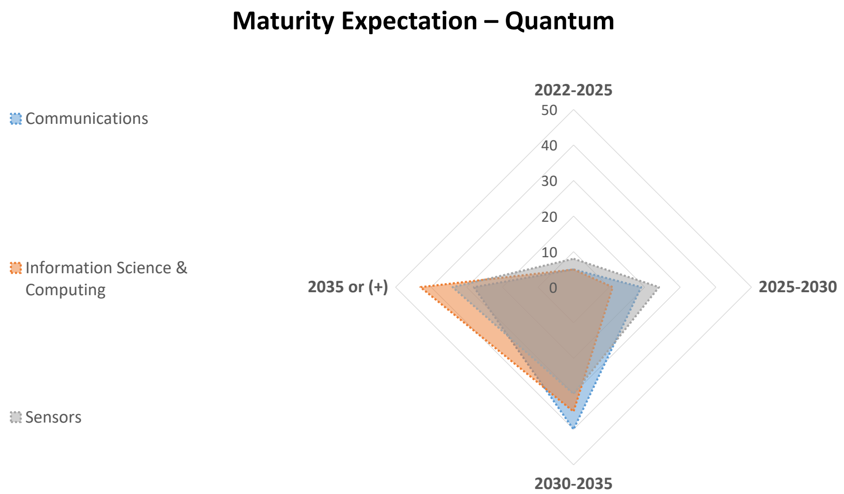


Sensors

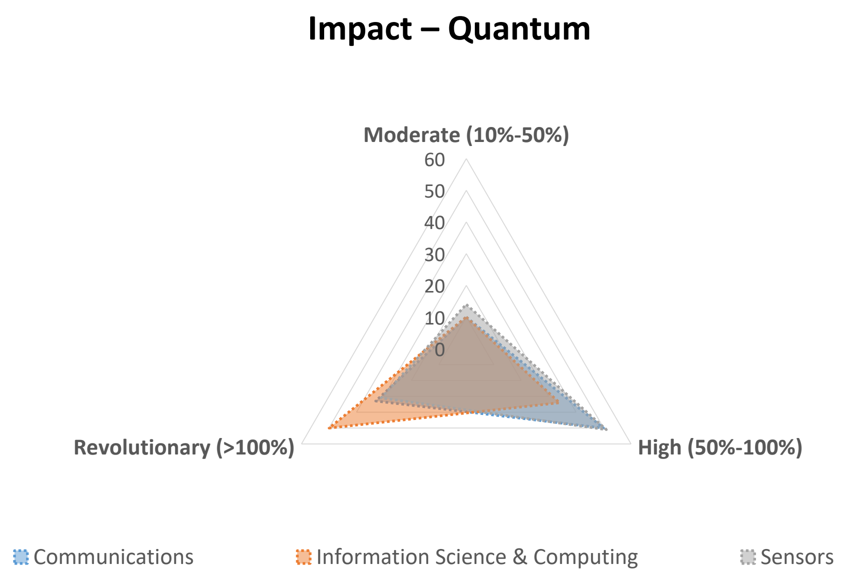




(a) QUANTUM - TRL).



(b) QUANTUM - Maturity).



(c) QUANTUM - Impact).

Figure K.8: *QUANTUM - STO Survey Results*

Robotics & Autonomous Systems (RAS)

Table K.17: *Robotics and Autonomous Systems (RAS) 2023 - 2043.*

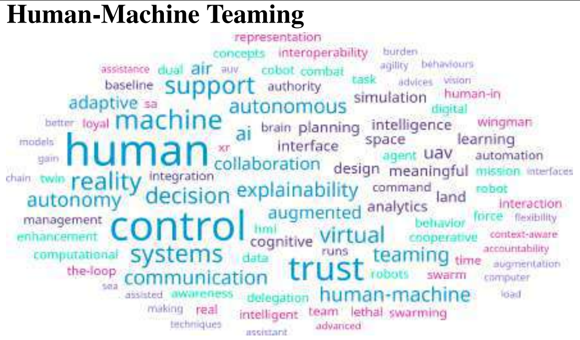
EDT	Technology Focus Areas	Impact	TRL	Horizon
RAS	Counter RAS	High	3-4	2030-2035
	Enhanced RAS	High	5-6	2025-2030
	Human-Machine Teaming	High	3-4	2030-2035

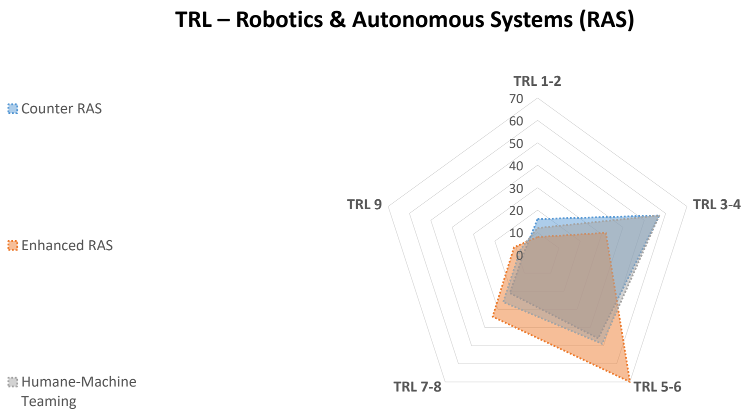
Table K.18: *RAS - Keywords*

Counter-RAS

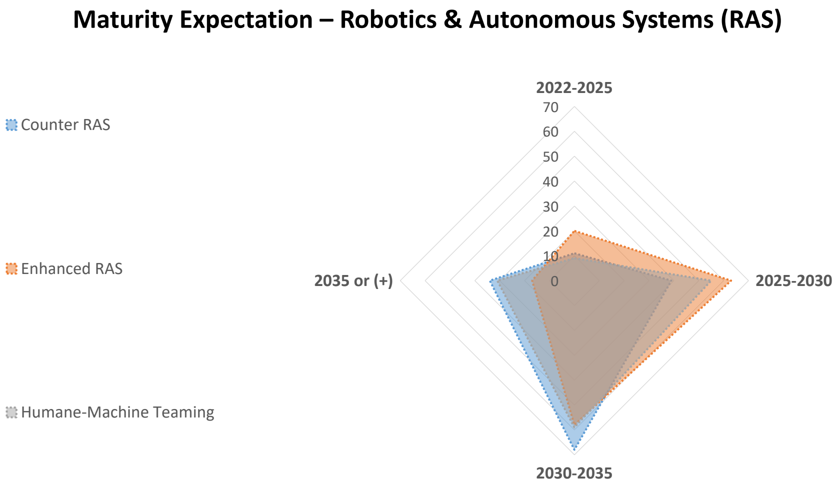
Enhanced RAS

Human-Machine Teaming

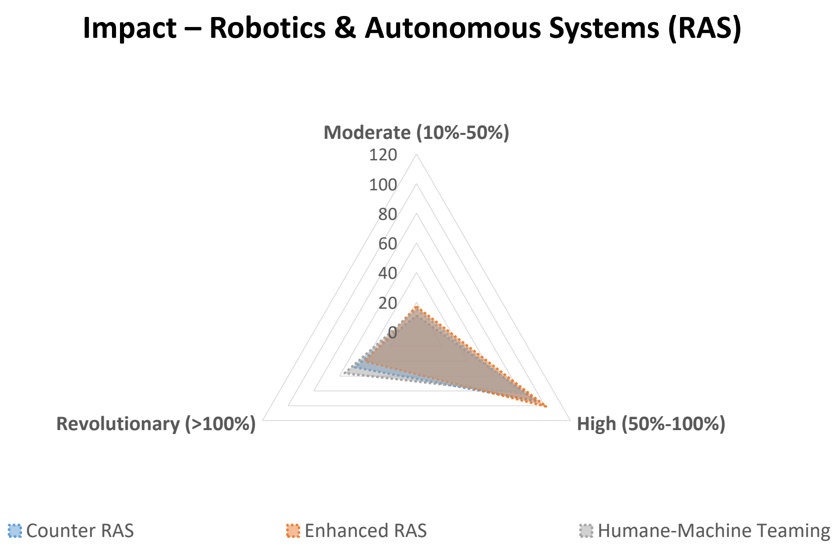




(a) RAS - TRL).



(b) RAS - Maturity).



(c) RAS - Impact).

Figure K.9: *RAS - STO Survey Results*

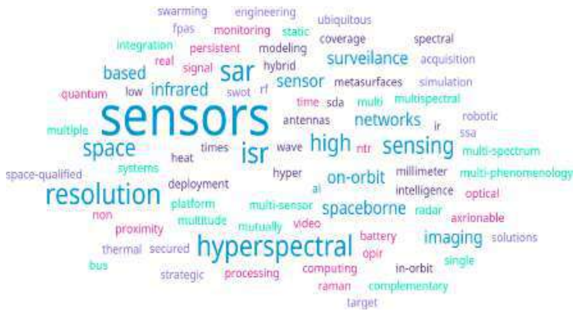
Space

Table K.19: Space Technologies (ST) 2023 - 2043.

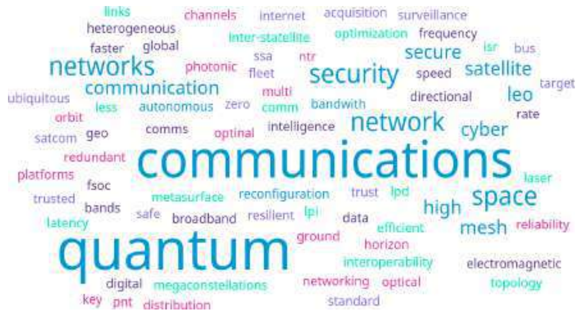
EDT	Technology Focus Areas	Impact	TRL	Horizon
Space	Communications	High	9	2022-2025
	Counter Space	High	5-6	2030-2035
	Platforms	High	9	2022-2025
	Propulsion & Launch	High	9	2022-2025
	Sensors	High	7-8	2022-2025

Table K.20: SPACE - Keywords

Sensors



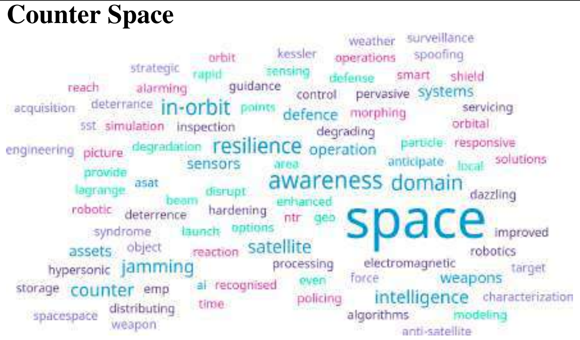
Communications

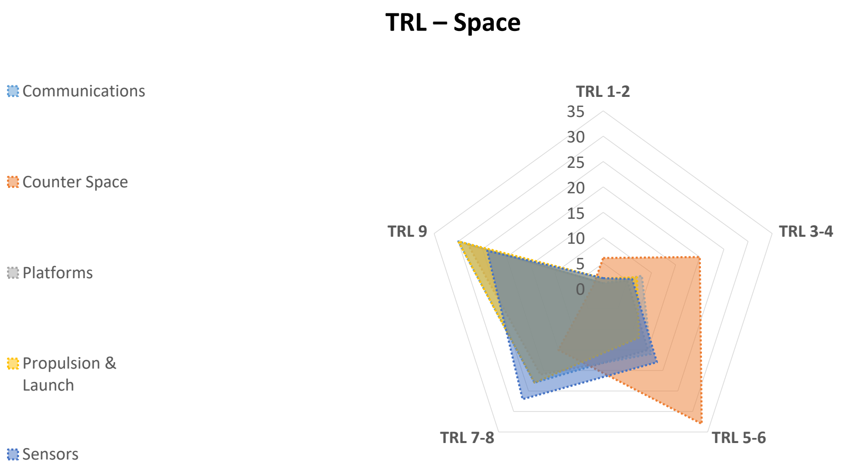


Platforms

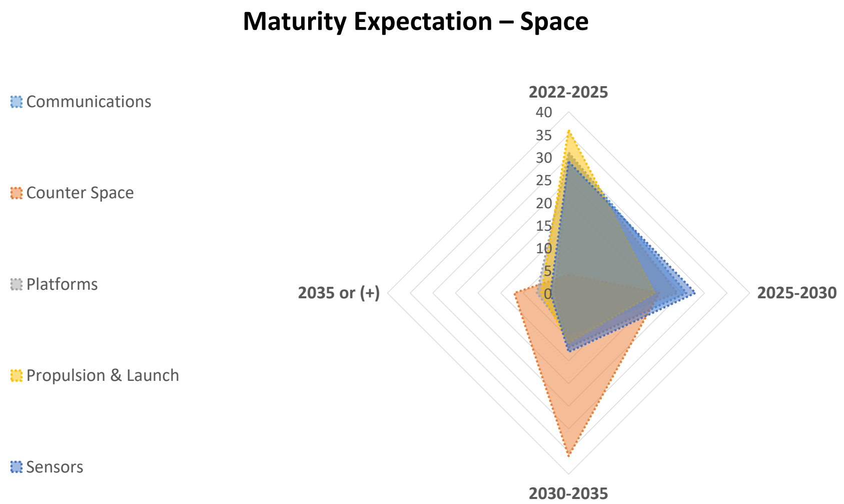
Propulsion

Counter Space

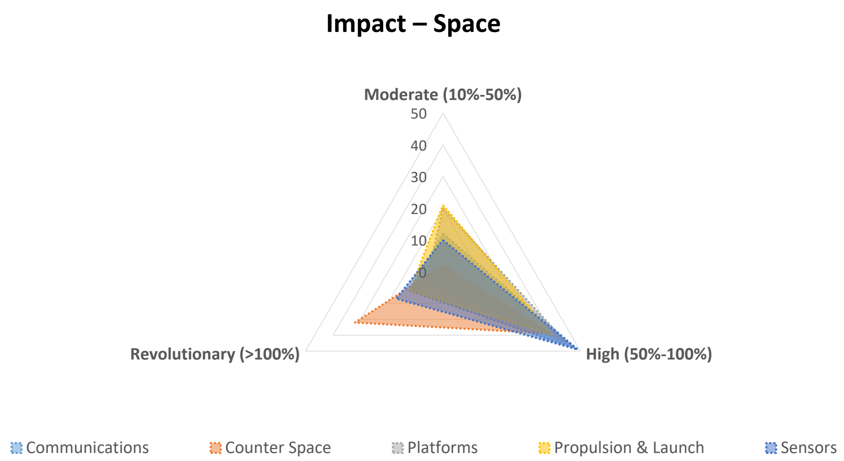




(a) SPACE - TRL).



(b) SPACE - Maturity).



(c) SPACE - Impact).

Figure K.10: *SPACE - STO Survey Results*

L. S&T Ecosystem Analysis Model (STEAM)

The Science & Technology Ecosystem Analysis Model (STEAM) aims to measure and monitor the global S&T landscape focusing on S&T developments across EDTs and beyond. Through AI and Machine Learning (ML), STEAM allows the STO to support EDTs *"weak signals"* assessment of meta-studies, national programs, selected reports, and quantitative analysis of publication and patent databases. More explicitly, STEAM allows the STO to observe different parameters to assess the status of the different EDTs. These parameters include:

- **Trends over Time**: This section provides insights regarding the weight of a given technology compared to the total volume of EDT-related publications.
- **Leading Countries**: By categorising the publications according to the nationality of the authors, we can detect weak signals regarding the alignment of national priorities.
- **Leading Institutions**: Through the categorisation of the publications according to the employer of the authors, we can detect weak signals regarding the alignment of national priorities.
- **Keywords**: The information compiled in these visualisations provides valuable information regarding the research trends across the publications.

STEAM is a work in progress. Once the product is adjusted, its results will be compiled into an independent report. In order to demonstrate its potential, you will find a brief demonstration on Volume 1, and more in depth use-case immediately below on **Artificial Intelligence** (AI). The results on AI are based on more than 656,000 publications aligned to AI that were produced in the time frame between 2018 and 2021.

Artificial Intelligence

Trends over Time

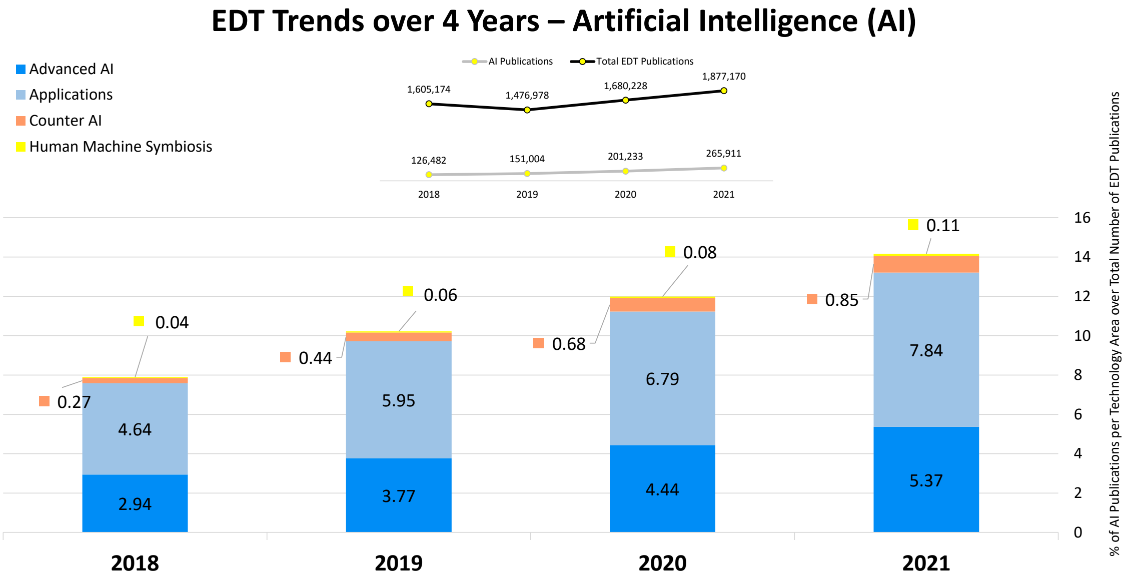


Figure L.1: STEAM - Artificial Intelligence - Trends over Time

Leading Countries

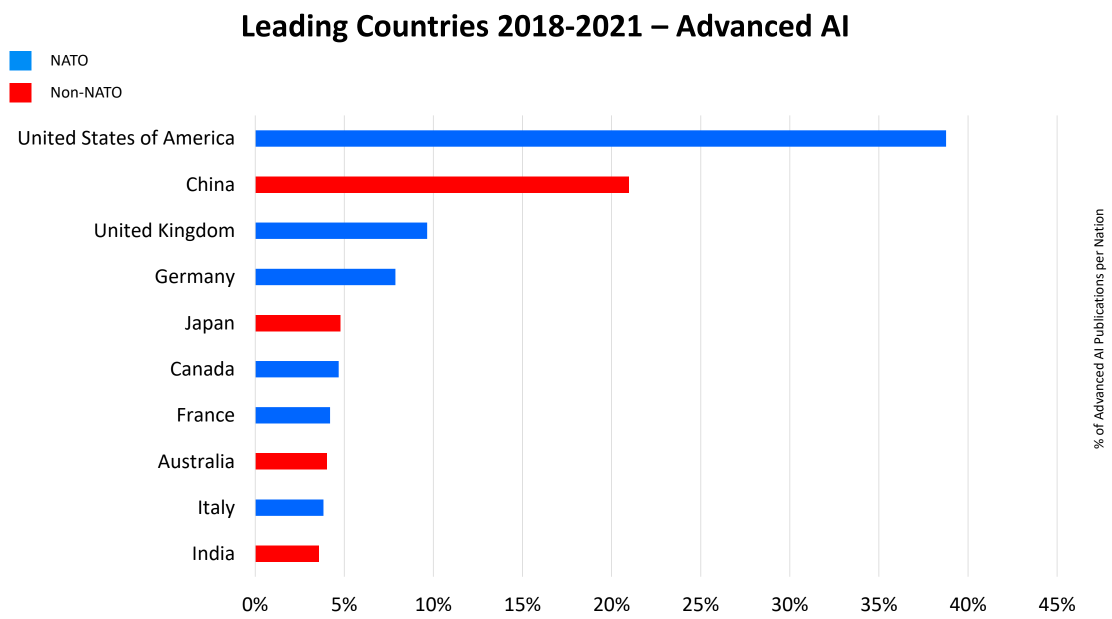


Figure L.2: *STEAM - Artificial Intelligence - Advanced AI - Top Nations*

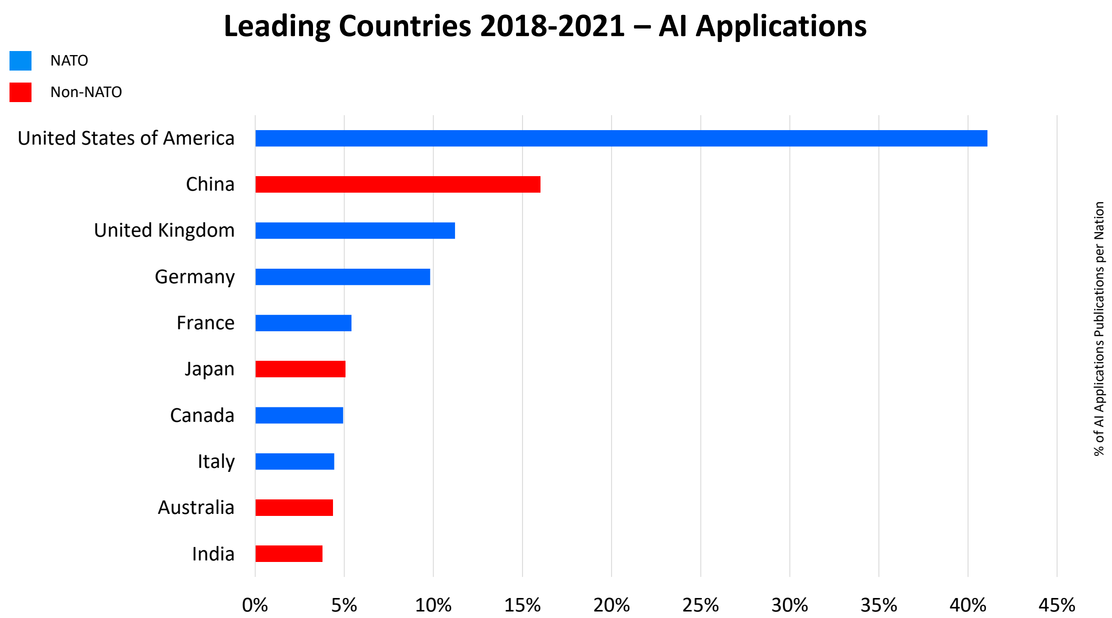


Figure L.3: *STEAM - Artificial Intelligence - AI Applications - Top Nations*

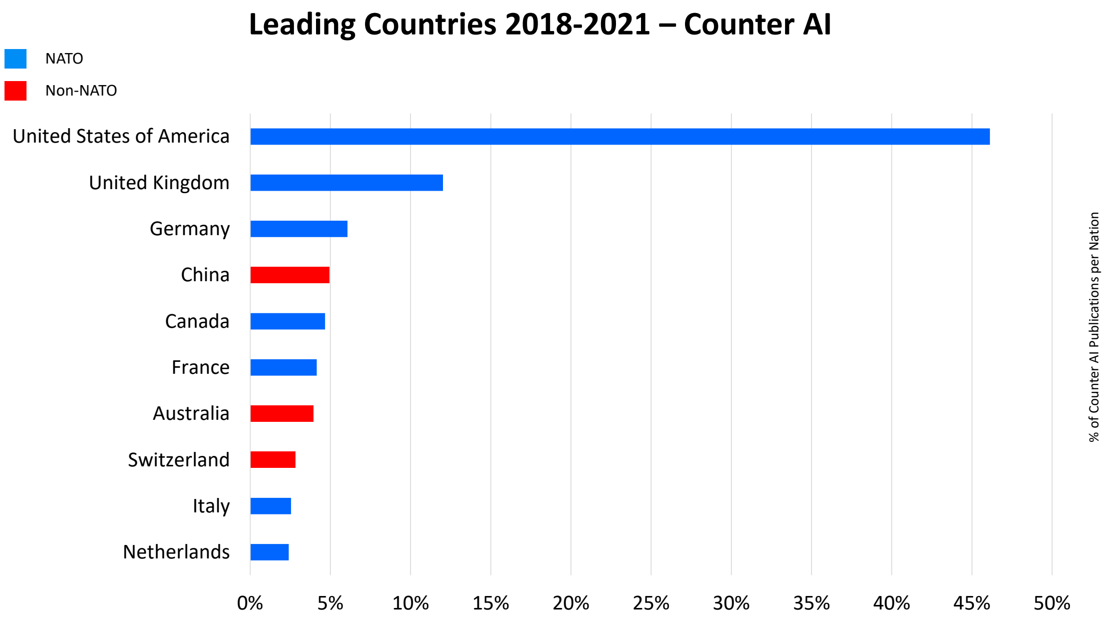


Figure L.4: *STEAM - Artificial Intelligence - Counter AI - Top Nations*

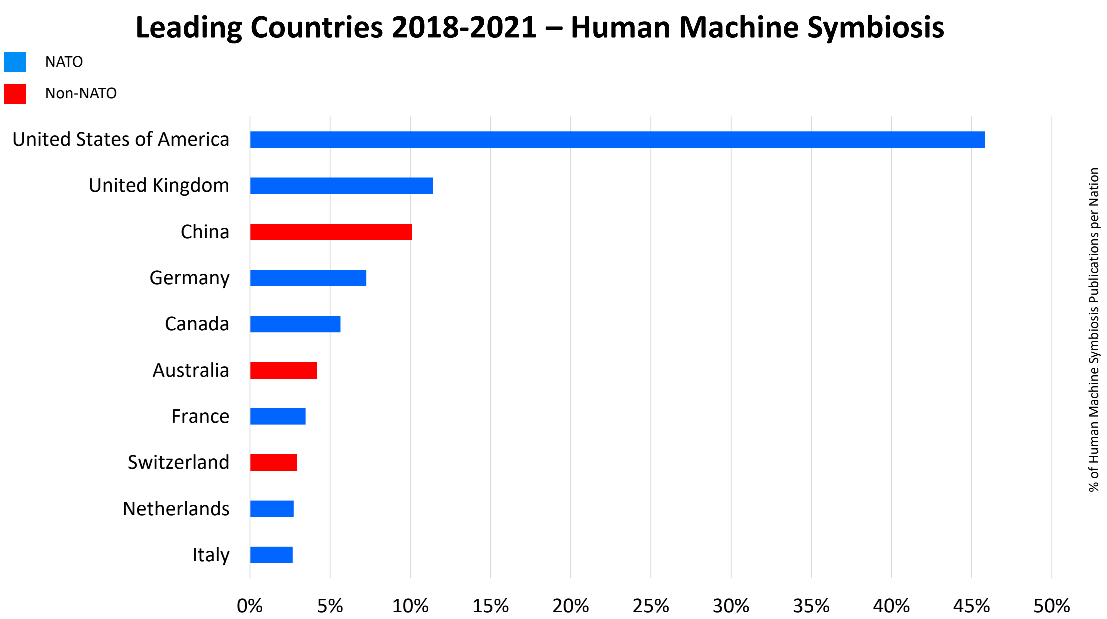


Figure L.5: *STEAM - Artificial Intelligence - Human Machine Symbiosis - Top Nations*

Leading Institutions

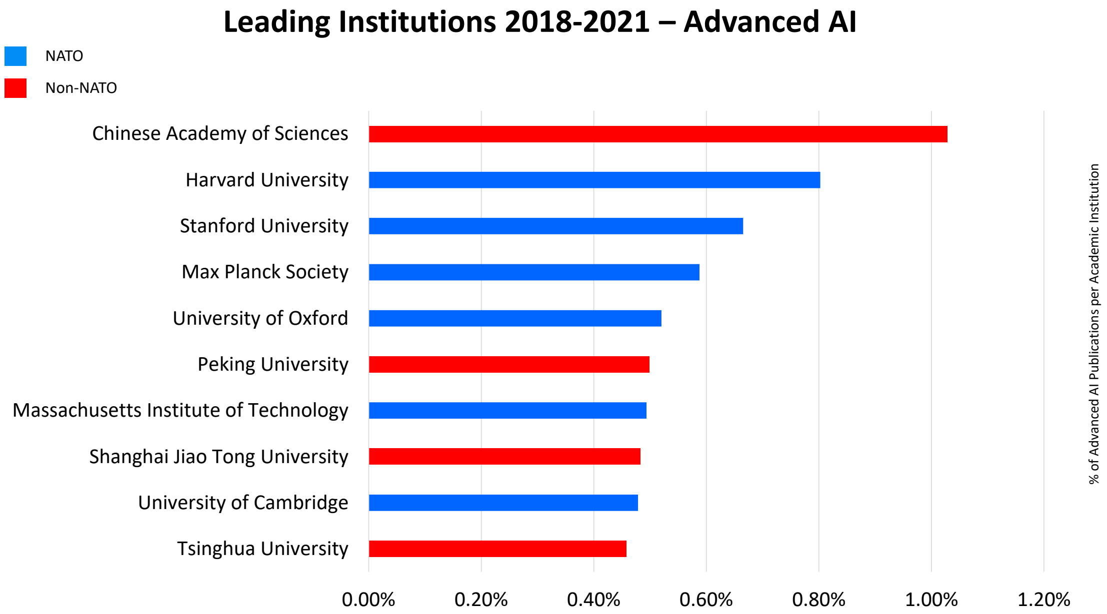


Figure L.6: *STEAM - Artificial Intelligence - Advanced AI - Top Institutions*

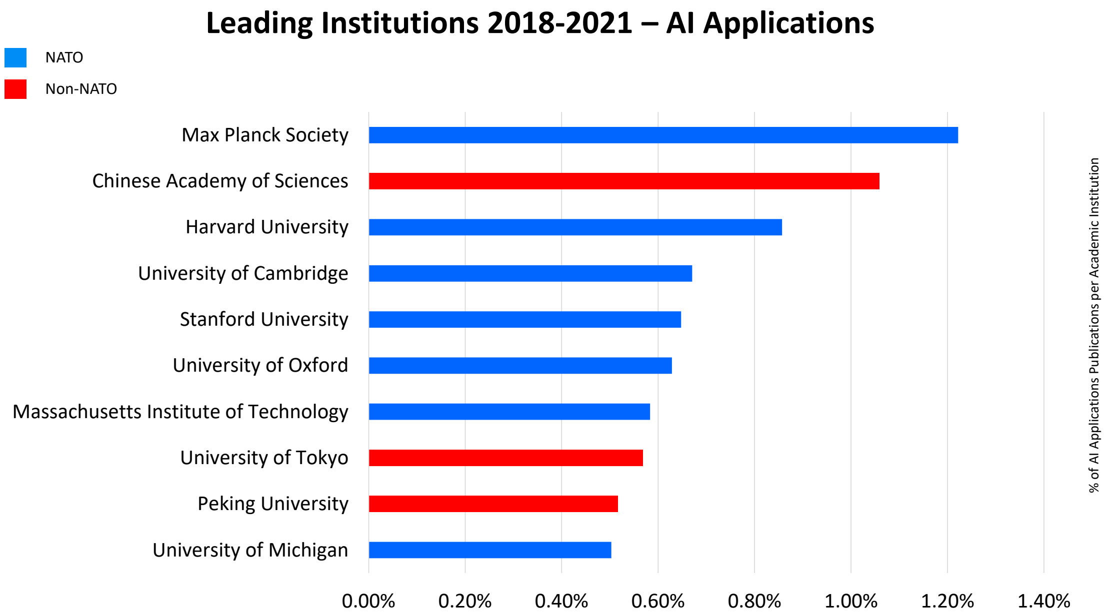


Figure L.7: *STEAM - Artificial Intelligence - AI Applications - Top Institutions*

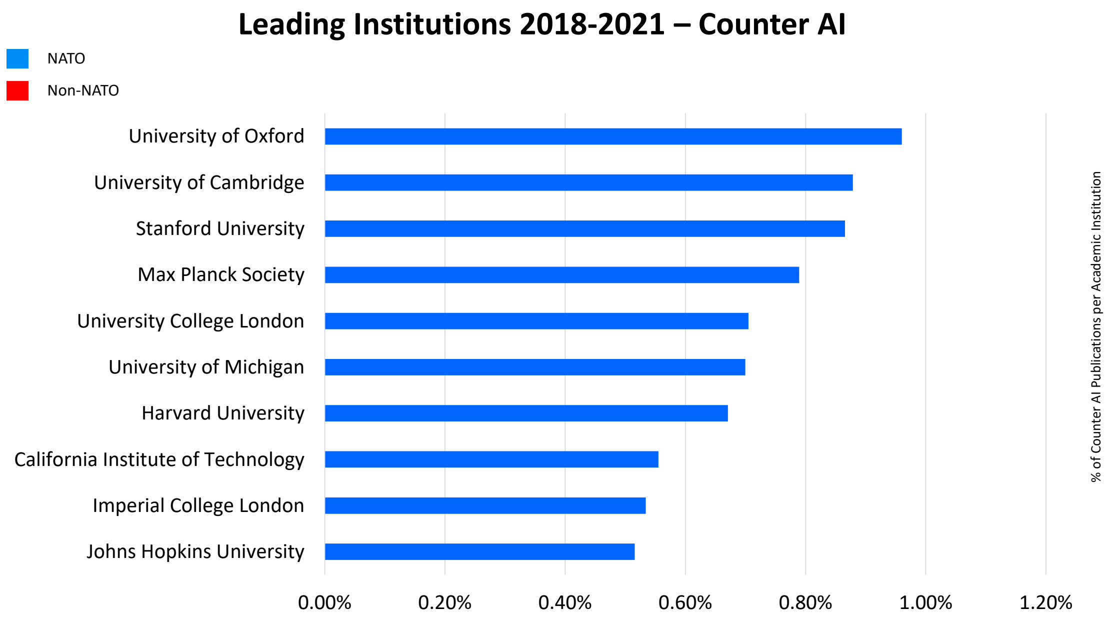


Figure L.8: *STEAM - Artificial Intelligence - Counter AI - Top Institutions*

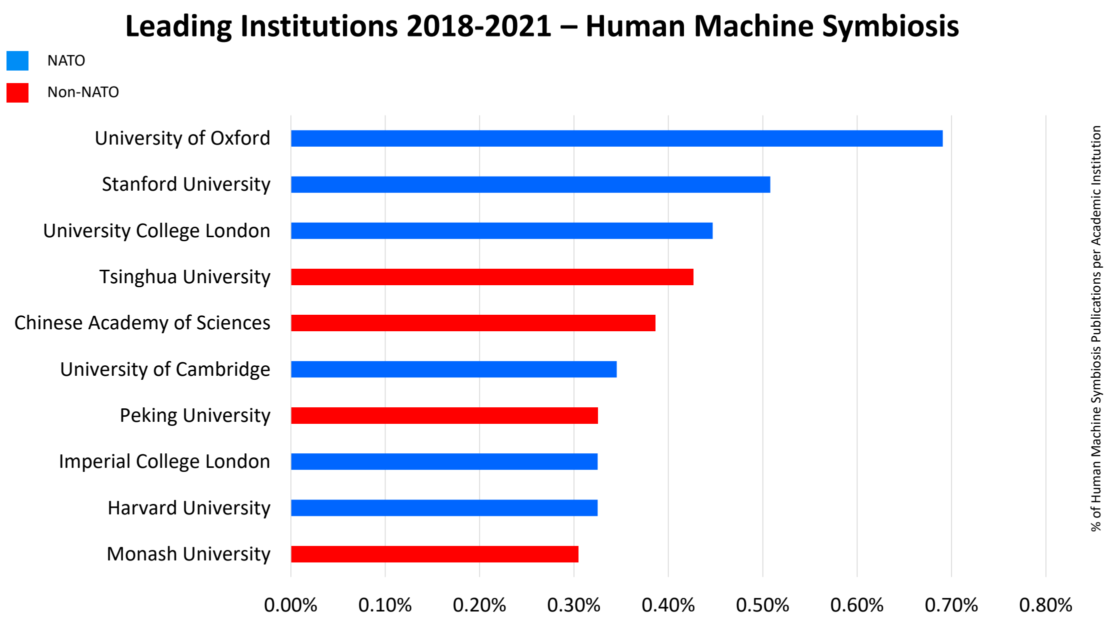


Figure L.9: *STEAM - Artificial Intelligence - Human Machine Symbiosis - Top Institutions*

Keywords

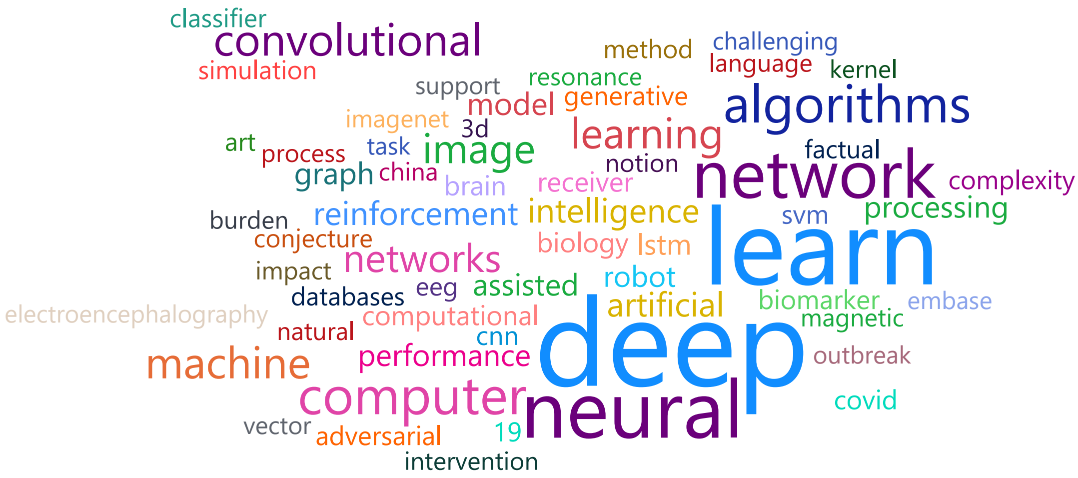


Figure L.10: STEAM - Artificial Intelligence - Advanced AI - Keywords

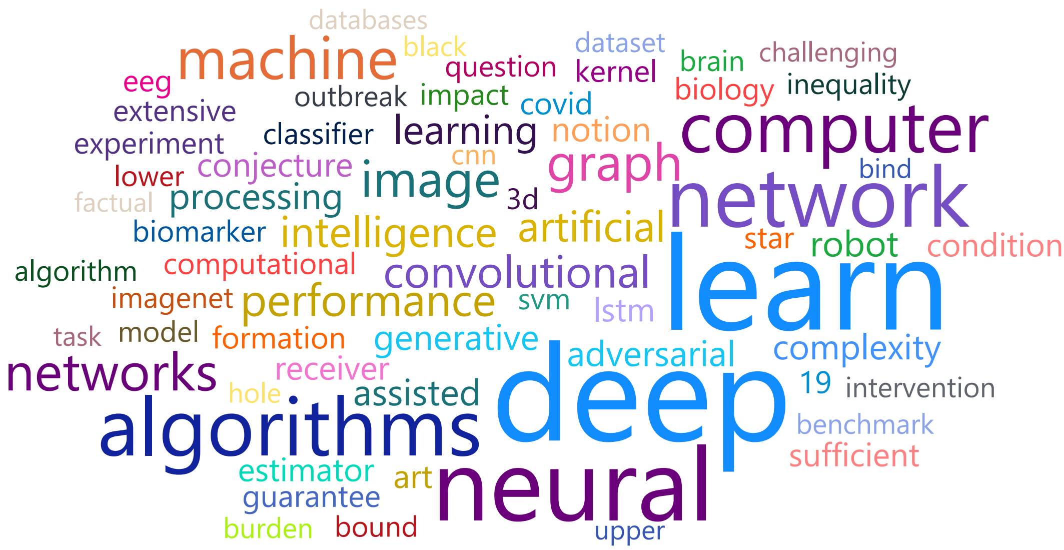


Figure L.11: STEAM - Artificial Intelligence - AI Applications - Keywords

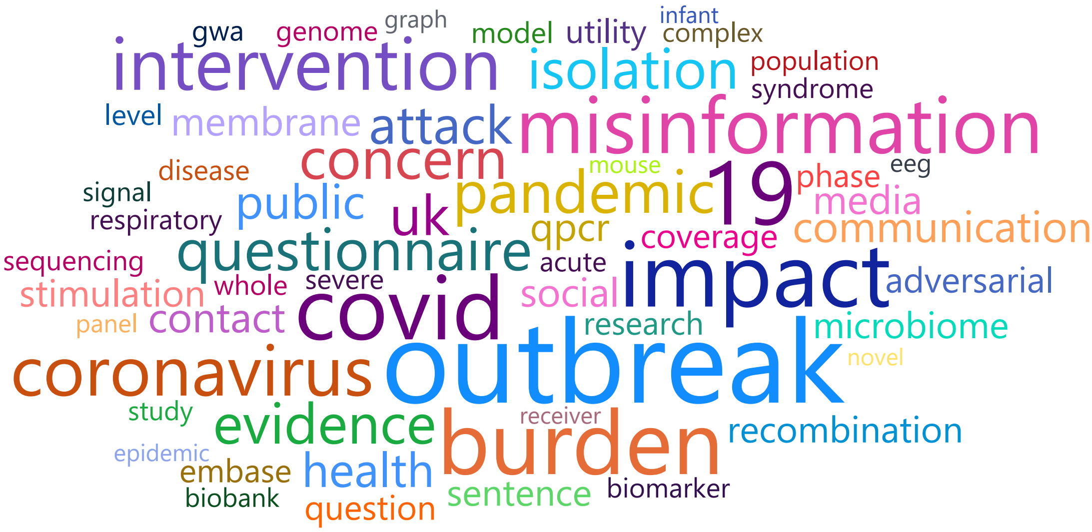


Figure L.12: STEAM - Artificial Intelligence - Counter AI - Keywords

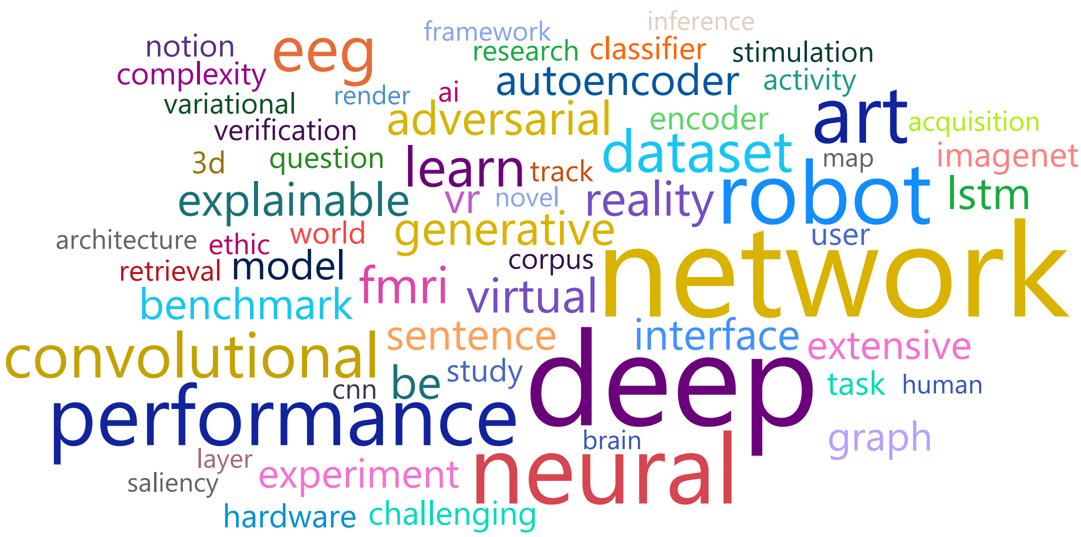
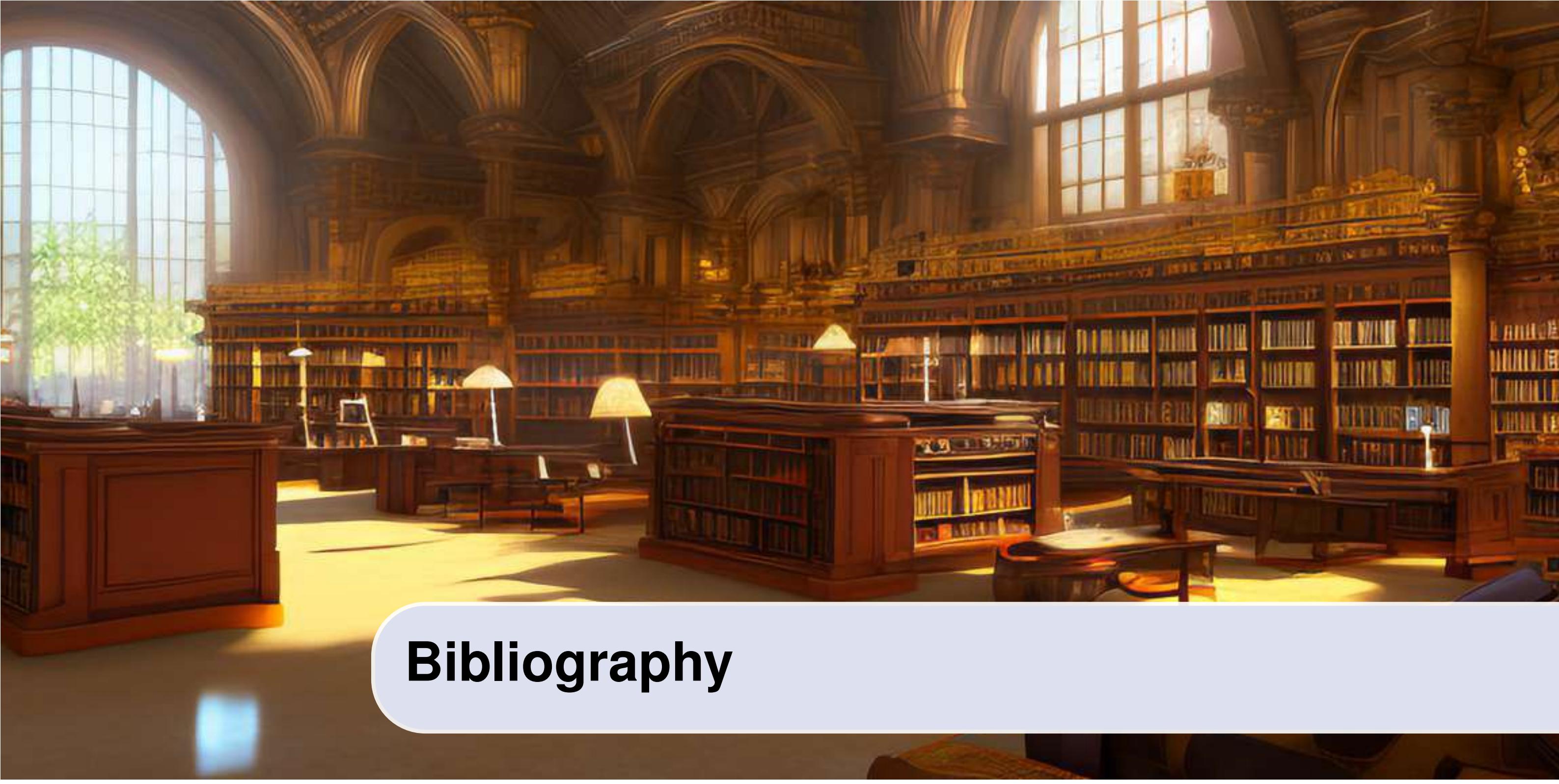


Figure L.13: STEAM - Artificial Intelligence - Human Machine Symbiosis - Keywords



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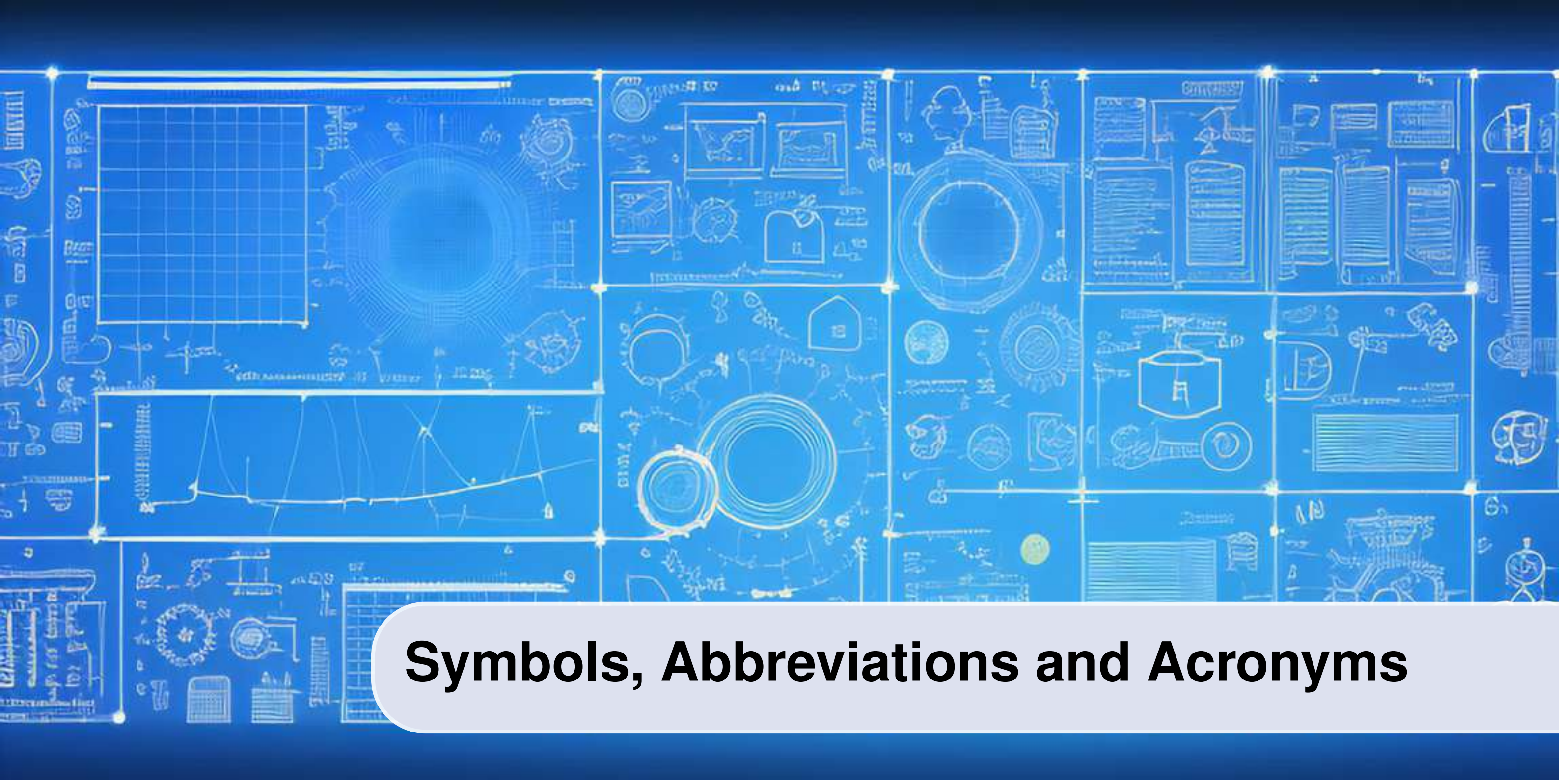

Symbols, Abbreviations and Acronyms

$\hbar$	$h/(2\pi)$
c	Speed of Light in a Vacuum ($2.99792458 \times 10^{+8} m/s$)
h	Planck Constant ($6.62607004 \times 10^{-34} m^2 kg/s$)
2-D *or* 2D	2-Dimensional
3-D *or* 3D	3-Dimensional
4-D *or* 4D	4-Dimensional
5G	Fifth Generation (Wireless Technologies)
5V	Volume, Velocity, Variety, Veracity and Visualisation (Challenges of Big Data)
A2AD *or* A2/AD	Anti-Access and Area Denial
ACT	Allied Command Transformation
ADF	Australian Defence Force
AFRL	Air Force Research Lab (USA)
AGI	Artificial General Intelligence
AI	Artificial Intelligence
AI HLEG	Artificial Intelligence High Level Experts Group
AIoT	Artificial Intelligence of Things
AIS	Automatic Identification System
AM	Additive Manufacturing
AMRG	Additive Manufacturing Research Group
ARL	Army Research Lab (USA)
ASAT	Anti-Satellite Weapons

ASW	Anti-Submarine Warfare
BDA	Battle Damage Assessment
BDAA	Big Data and Advanced Analytics
BHET	Bio and Human Enhancement Technologies
BLUE	Friendly Forces
C2	Command & Control
C3	Consultation, Command and Control
C4ISR	Command, Control, Communications, Computers (C4) Intelligence, Surveillance and Reconnaissance (ISR)
CBRN	Chemical, Biological, Radiological and Nuclear
CBRNE	Chemical, Biological, Radiological, Nuclear, and Explosive
CI	Computational Imaging
CMRE	Centre for Maritime Research and Experimentation
COA	Courses of Action
COP	Common Operating Picture
CPoW	Collaborative Program of Work
CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
CSBA	Center for Strategic and Budgetary Assessments
CWA	Chemical Warfare Agent
D3TX	Disruptive Technology Table-Top Exercise
DARPA	Defense Advanced Research Projects Agency (US)
DCDC	Development, Concepts and Doctrine Centre
DEW	Directed Energy Weapon
DGA	Direction Générale de L'armement
DGRIS	Direction Générale des Relations Internationales et de la Stratégie
DIA	Defense Intelligence Agency
DIM	Deception, Identification & Monitoring
DIME	Diplomatic, Information, Military and Economic
DNA	Deoxyribonucleic Acid
DND	Canadian Department of Defence
DOD	US Department of Defence
DOTMLPF-I	Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities and Interoperability

DRDC	Defence Research and Development Canada
DST	Defence Science and Technology Group (AUS)
dstl	Defence Science and Technology Laboratory (UK)
DSTO	Defence Science and Technology Organisation (AUS)
E&EM	Electronics & Electromagnetics
EDA	European Defence Agency
EDT	Emerging And/Or Disruptive Technology
ELINT	Electronic Intelligence
EM	Electromagnetic
EO	Electro-Optical
EOD	Explosive Ordnance Disposal
EW	Electronic Warfare
FAS	Federation of American Scientists
FLIA	Foundation for Law & International Affairs
fm	Femtometer $(10^{-15}m)$
FOI	Foi Totalförsvarets Forskningsinstitut / Swedish Defence Research Agency
GAI	Generalised Artificial Intelligence
GAN	Generative Adversarial Network
GAO	(US) General Accounting Office
GDP	Gross Domestic Product
GEO	Geosynchronous Equatorial Orbit
GNSS	Global Navigation Satellite System
GoC	Government of Canada
GPS	Global Positioning System
HALE	High Altitude Long Endurance
HCM	Hypersonic Cruise Missile
HDMS	His/Her Danish Majesty's Ship
HEO	Highly Elliptical Orbit
HET	Human Enhancement Technologies
HGV	Hypersonic Glide Vehicle
HT	Hypersonic Technologies
I2D2	Intelligent, Interconnected, Distributed & Digital

IED	Improvised Explosive Device
IoT	Internet of Things
IP	Intellectual Property
IR	Infrared
IS/ESC	NATO International Staff / Emerging Security Challenges
ISR	Intelligence, Surveillance and Reconnaissance
ISTAR	Intelligence, Surveillance, Targeting and Reconnaissance
ITW&AA	Integrated Tactical Warning and Attack Assessment
JAIC	(NATO) Joint Artificial Intelligence Center
JALLC	(NATO) Joint Analysis and Lessons Learned Centre
JAPCC	(NATO) Joint Air Power Competence Centre
LEO	Low Earth Orbit
LIDAR	Light Detection and Ranging
M&S	Modelling and Simulation
Mach 1	Speed of Sound (340.3 m/s; 1,235 km/s; 767 mph) In Dry Air at Mean Sea Level and Standard Temperature of 15°C)
MASINT	Measurement and Signature Intelligence
MC	Military Committee
MCM	Mine Countermeasures
MEO	Medium Earth Orbit
MIMO	Multiple-Input and Multiple-Output,
MIoP	Military Instruments of Power
ML	Machine Learning
MOD	(UK) Ministry of Defence
mTBI	Mild Traumatic Brain Injury
NAC	North Atlantic Council
NASC	Naval Air Systems Command
NATO	North Atlantic Treaty Organization
NCIA	NATO Communication and Information Agency
NDPP	NATO Defence Planning Process
NGO	Non-Governmental Organisations
nm	Nano-Metre ($10^{-9}m$)

NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council (Canada)
OCS	NATO Office of The Chief Scientist
OECD	The Organisation for Economic Co-Operation and Development
OGD	Other Government Departments
ONR	Office of Naval Research (USA)
OODA	Observe, Orient, Decide, and Act
OR&A	Operational (Operations) Research & Analysis
OTH	Over-The-Horizon
PAL	Phase Alternating Line
PCE	Physiological and Pharmacological Cognitive Enhancements
PCL	Passive Coherent Location (Radar)
PLA	People's Liberation Army
pm	Picometer ($10^{-12}m$)
PNT	Positioning, Navigation and Timing
PRC	People's Republic of China
PTSD	Post-Traumatic Stress Disorder
QC	Quantum Communication
QIS	Quantum Information Science
QKD	Quantum Key Distribution
QO	Quantum Optics
QT	Quantum Technologies
R&D	Research and Development
RAP	Recognised Air Picture
RAS	Robotics and Autonomous Systems
RCAF	Royal Canadian Air Force
RDDC	Recherche et Développement Pour La Défense Canada
RDS	Research and Development Statistics
RED	Hostile Forces
RF	Radio Frequency
ROE	Rules of Engagement
RSGB	Royal Society (Great Britian)

S-AIS	Satellite - Automatic Identification System
S&T	Science and Technology
SA	Situational Awareness
SACEUR	Supreme Allied Commander Europe
SACT	Supreme Allied Commander Transformation
SAR	Synthetic-Aperture Radar
ST	Space Technologies
STO	Science & Technology Organization
SWaP-C	Size, Weight, Power and Cost
TBM	Theatre Ballistic Missile
TCPED	Tasking, Collection, Processing, Exploitation, and Dissemination
TFA	Technology Focus Area
THz	Terahertz ($10^{12} Hertz$)
TOE	Targets of Emphasis
TRADOC	U.S. Army Training and Doctrine Command
TRL	Technology Readiness Levels
TSTO	Two State to Orbit
TWC	Technology Watch Card
UAV	Unmanned Air Vehicles
UCAV	Unmanned Combat Aerial Vehicle
UGV	Unmanned Ground Vehicle
UK	United Kingdom
UMS	Unmanned Maritime Systems
UNESCO	United Nations Educational, Scientific and Cultural Organization
US	United States
USA	United States of America
USD	US Dollars
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicles
UV	Ultraviolet
UxV	Unmanned Vehicles
vKHS	Von Kármán Horizon Scan

vKI	Von Kármán Institute
VV&A	Verification, Validation, & Accreditation
WEF	World Economic Forum
µm	micrometer $(10^{-6}m)$


ASSESSMENT
TECHNOLOGIES
TECHNOLOGY
TRAINING
MODELLING
NATO
APPLICATIONS
VEHICLES
SUPPORT
MILITARY
EO
IR
RADAR
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SIMULATION
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