Part IV

FIELDS OF INNOVATIONS AND THEIR LEGAL REGIMES

IV.1

DUAL CIVILIAN AND MILITARY USE TECHNOLOGIES: EMERGING AND DISRUPTIVE TECHNOLOGIES

Chapter 6

The Dual Use of Civilian and Military Technologies in the Battlefield of the Future

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Abstract

This chapter discusses the reasons for and outcomes of the inevitable and dynamic transition to a highly technological future battlefield that will dramatically affect all armies worldwide. Military technology and progress motivation are specific and backed by long-term incremental development, leading to the achievement of pragmatic goals, which are deeply coded in the human genome and are similar for some military and civilian domains, such as battlefields and businesses. This chapter presents fundamental evidence that leads to a better understanding of particular aspects of modern warfare and the technological nature of future conflicts. It discusses the complex relationship between cutting-edge military technology and dual-use aspects and explores the ethical implications and potential future trajectories of such interconnected technological developments.

Keywords: Future Battlefield, Dual-use aspects, Technological Warfare

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1. Introduction

In an ever-evolving global technological landscape, dual-use innovations weave a complex pattern, serving both civilian and military needs. These tools and systems, which are adaptable to both peaceful applications and strategic military operations, are a testament to human ingenuity.[1] One area where this intersection is particularly profound is in the field of advanced military technologies. While they may originate in defence laboratories with national security and warfare superiority as their objectives, the collateral effects of these military innovations often reshape civilian industries. From the precision of Global Positioning Systems (GPS) to the robustness of aerospace materials, military-derived technologies have, over time, become indistinguishably linked to everyday life. With the advancement of technology, the concept of a battlefield has undergone tremendous change.[2] It now encompasses not only physical locations, but also virtual and digital spaces. Dual-use technologies, with civilian and military implications, have significantly driven this transformation. These technologies shape military strategies, making it crucial to master the digital and technological domains in addition to having physical strength. The conventional interpretation of battlefields as complex terrains dotted with trenches, artillery, and infantry – a depiction deeply ingrained in our minds through history books and war movies – is now undergoing a significant transformation. This traditional image is being reshaped and redefined in the current era of rapid technological advancement.

The term "technological battlefield" refers to the arena in which advanced technologies significantly shape modern warfare, security operations, and defence strategies, powered by artificial intelligence, such as cyber warfare tools, unmanned autonomous systems, space technologies, and advanced communication systems. Significant advantages include enhanced real-time decision-making, remote warfare capabilities, precision targeting, and vast amounts of data that can be collected and analysed. However, with these developments come new vulnerabilities and challenges. Therefore, the technological battlefield demands not only advanced tools, but also new doctrines, strategies, approaches, and a deep understanding of the digital and technological environment that is now interwoven with traditional warfare. Based on current technology and trends in military operations, the following areas of evolution can be considered critical for the technological transformation of the future battlefield:[3]

- Automated and artificial intelligence (AI)-driven warfare: The rise of drones, autonomous vehicles, and AI-driven surveillance systems represents another layer of the technological battlefield. AI algorithms can analyse vast datasets

1 Scharre, 2023, p. 46.
2 Scharre, 2019, pp. 89–112.
3 NATO EDT's, 2024.

for intelligence gathering, and automated drones can execute precision strikes with minimal human intervention.

- Digital frontlines: Cyberspace is emerging as the foremost technological battlefield. Cyber warfare does not involve tanks and troops but is characterised by the presence of hackers, malware, and digital espionage. Nations are investing heavily in the development of sophisticated cyber weapons and defence systems.
- Electromagnetic spectrum and information warfare: Control over the electromagnetic spectrum, encompassing radio waves, microwaves, and visible light, is crucial. Modern information warfare encompasses tactics such as jamming enemy communications, disseminating false information with deep fakes, and influencing public opinion through social media campaigns.
- Dominance in outer space: Once the final frontier of exploration, space is now a strategic battleground. Satellites are essential for communication, navigation, and surveillance and are potential targets. Anti-satellite weapons and satellite defence systems have marked a new age in the space race.
- Biotechnological warfare: Advancements in biotechnology have raised concerns regarding its potential misuse. Engineered pathogens or genetic warfare may become tools in the arsenals of nations or rogue entities, making labs as significant as missile silos.
- Quantum frontiers: As nations race to develop quantum computers, there is a looming battle over quantum encryption and decryption. Mastery of quantum technology may soon become synonymous with global dominance.

In conclusion, the technological battlefield is multifaceted, dynamic, and continually evolving. While traditional warfare objectives, such as dominance, defence, and deterrence, remain unchanged, the tools and terrains have been revolutionised.[4] As technology continues its persistent march, the lines between combat zones and civilian spaces blur, calling for extensive understanding and innovative strategies to navigate this new type of warfare.

Dual-use technology plays a crucial role in the complex relationship between technological progress and strategic military evolution. Its pervasiveness is significant across diverse fields, from the AI domain to material science, and it can fundamentally change conflict dynamics. Dual-use technologies possess high flexibility and blur the lines between peace and war. They have excellent potential to significantly improve operational efficiency, precision, and responsiveness, enabling militaries to collect and analyse vast amounts of data, obtain real-time pictures of joint operations, and develop innovative tactics and strategies. However, the dual-use nature of these technologies raises concerns regarding their proliferation, unintended consequences, and the likelihood of militarising civilian technological advancements. Even though the acceleration of the military technology race offers

4 Scharre, 2023, pp. 11–16.

many complex opportunities and challenges for nations engaged in military affairs, it most likely shape the (inevitable) future world evolvement.

Military history is a narrative of relentless technological innovation. As societies progress, their instruments of war advance in tandem, catalysing profound transformations in battle strategies, tactics, and, ultimately, the outcomes of conflicts. Many military technologies have fundamentally impacted the army and civilian domains, often in ways that blur the lines between these sectors. History demonstrates the far-reaching and frequently unexpected ways in which military innovations can affect civilian life and vice versa. Examples of where dual-use technology has been helpful for both civilian and military purposes could include the following:

Satellite communications Based on satellites positioned in geostationary, medium-, or low-Earth orbits, can transfer data across vast distances. They are situated approximately 35,786 km above the Equator. This technology is crucial for various purposes, including television broadcasting, telephone calls, radio and internet access, military operations, and the emergency sector, connecting disconnected geographical regions. Satellite technology has become a fundamental force in the modern interconnected world.

Long-range earth surveillance enables continuous operational environmental monitoring and is crucial in modern warfare, offering tactical advantages in various combat scenarios. On the civilian front, the same technology has been extensively used in environmental monitoring, disaster management, and urban planning. The utilisation of precision farming methods to enhance crop productivity and resource management holds immense significance in agriculture. The integration of long-range Earth surveillance technology from the military to civilian sectors underscores its adaptability and the possibility of technological breakthroughs that cater to broader societal requirements. This emphasises the interdependence of the military and civilian progress.

Global Positioning System (GPS), initially designed by the U.S. Department of Defense for military navigation, has profoundly transformed civilian life worldwide. In warfare, it provides extreme precision in navigation and targeting, which had not been achieved by any alternative, and significantly supports the military in operation. On the civilian front, GPS has revolutionised numerous industries, from transportation to telecommunications, enabling precise location tracking for navigation, logistics, and personal electronic devices. This technology represents one of the best examples of how military innovation can transcend its initial purpose and become an indispensable tool in everyday civilian life, illustrating the profound impact of dual-use technologies.

The Internet, another crucial example of dual use, was launched as a military initiative called Advanced Research Projects Agency Network (ARPANET) in the late 1960s, initially aimed at maintaining dependable communication during nuclear threats. This early network was essential for enabling long-distance information exchange between computers and served as a vital tool for military purposes. Over time, this technology has evolved beyond its defence-oriented origin and has become a critical part of the infrastructure for almost every aspect of modern life, demonstrating the transformative potential of dual-use technologies.

Unmanned aerial vehicles (UAVs), commonly known as drones, were initially developed for military purposes and have become essential to modern warfare. This technology outperforms other alternatives in military tasks such as surveillance, reconnaissance, and precision strikes. It has many civilian applications, such as aerial photography, precision agriculture, geographic surveying, and innovative delivery systems.

The development of *nuclear energy* can be traced back to World War II when the United States began the Manhattan Project, which culminated in the creation of atomic weapons. This crucial moment marked the birth of nuclear technology, which was initially intended for the purpose of destruction. Nuclear power plants have emerged as critical players in global energy production because they significantly reduce carbon emissions and reinforce energy security. This transition from wartime innovation to an important aspect of civilian infrastructure represents a significant example of dual-use.

Military medical research advancements in trauma care, prosthetics, and treatment for internal diseases[5] have substantially improved understanding of the requirements of civilian patients, including emergency medical response and rehabilitation.

It is also important to mention the transition of radar and sonar systems from military to civilian uses, such as air traffic control, weather monitoring, and oceanic research. Similarly, advanced materials such as Kevlar and carbon fibres, which were initially utilised in the space and military domains, are now commonly utilised in the private sector (sports equipment, automotive industry, etc.). Jet and rocket propulsion technologies, which are crucial in the military context, have also become integral to civilian air and space industries.

The list of dual-use technologies is long, and a detailed description is beyond the scope of this chapter. However, we should not forget essential areas where dual-use technologies have had a significant impact on both domains, such as robotics, biotechnology, energy storage and battery technology, quantum computing and communications, 3D printing and additive manufacturing, advanced sensors and imaging technologies, telecommunications advancements (e.g. 5G), and augmented and virtual reality (AR/VR). Understanding the dual-use nature of these technologies and their relationship to other non-technological issues is crucial for strategy and policy development.[6]

5 Liu, 2021.
6 Scharre, 2023, pp. 49, 166, 372.

2. Contemporary developments in NATO

The North Atlantic Treaty Organization (NATO) has always been at the forefront of leveraging advanced technology to ensure collective defence, crisis management, and cooperative security. Nevertheless, the reality differs for each Member State. As a result of the collapse of the Warsaw Pact and the corrosion of the Soviet Union's integrity, NATO lost its primary opponent, which has led to a significant erosion of defence capabilities over the last three decades. European armies suffered substantial budgetary constraints, a slowdown in military technological development, and a deterioration in operational readiness.

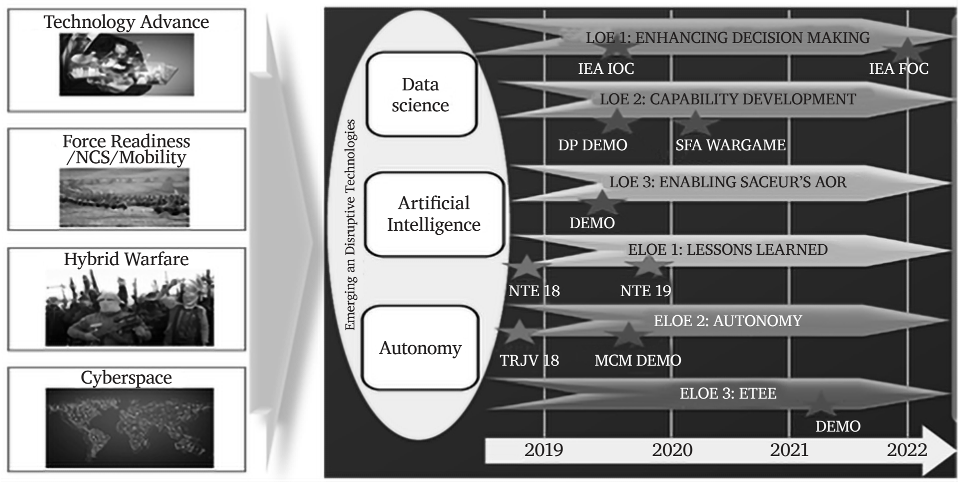
Arguments and prognoses regarding the technological nature of the future battlefield were present within NATO from the 1970s and continued until the beginning of the millennium. Serious discussions about the roles of advanced technologies, especially autonomous systems, started in 2012/2013, focused on the strategic implications of autonomous systems and specific guidelines for managing this field.[7]

In 2016, NATO recognised cyberspace as an operational domain and started reinforcing its cyber defence capabilities. This finding supports the idea that member nations fortify their resilience to counter digital threats. Subsequent progress within NATO, associated with advanced technologies, was introduced at the NATO 2018 Summit as a result of significant technological advancements in China and Russia. The Summit in Brussels was essential for addressing many challenging issues. Key topics included reinforcing defence commitments and increasing Member States' military spending to 2% of their GDP. The summit also dealt with evolving security challenges, such as cyber threats and terrorism, and Russia's growing hostility, especially in the context of its actions in Ukraine. Another significant step was the formal invitation to North Macedonia to begin accession talks, demonstrating NATO's continued expansion and adaptation. The summit highlighted the need for unity and adaptability among Member States to respond effectively to contemporary geopolitical challenges. This led to further discussions on enhancing NATO's readiness and response capabilities[8] in the context of supporting advanced technology development and introducing new and disruptive technologies, crucial for the future NATO evolvement, which led to a significant upgrade of NATO Lines of Effort (LOE).

7 NATO RTO – SAS 097 – *Robots underpinning future NATO Operations* (solved between 2012-2014). [Online]. Available at: https://cmp.felk.cvut.cz/natorobot/index.html (Accessed: 5 January 2024); *Multinational Capability Development Campaign Role of Autonomous Systems in Gaining Operational Access*. [Online]. Available at: https://www.act.nato.int/wp-content/uploads/2023/05/2023_Fact_Sheet_MCDC.pdf (Accessed: 5 January 2024); Kuptel and Williams, 2014, pp. 2–34; Williams and Scharre, 2015, p. 3.

8 NATO, 2018, Article 31.

Figure 1: NATO Summit – Lines of Effort Planned Evolvement, Director of the NATO Modelling and Simulation Centre of Excellence presentation, Steering Committee Meeting 2019



In 2019, space became an official NATO operational domain, highlighting NATO's commitment to addressing the challenges and opportunities presented by satellite communication, navigation, and surveillance. Another significant milestone for the alliance was the NATO Warfighting Capstone Concept (NWCC), which was approved in 2021 and is crucial for reinforcing the alliance's deterrence and defence position. It provides a forward-looking vision for sustaining and enhancing NATO's decisive military edge while adjusting its military capabilities up to 2040. The NWCC primarily addresses the emerging elements of the excessive power race. However, the ongoing conflict in Ukraine initiated by Russia emphasises that the traditional military force remains a crucial aspect of the current security landscape. Since the NWCC's endorsement, NATO has advanced its implementation across various domains, including significant political initiatives, to preserve its strategic superiority.

Last year, the NATO STO released the NATO Science & Technology Trends 2023-2043, comprehensively evaluating emerging and disruptive technologies (EDTs) and their potential impacts on NATO's military operations, defence capabilities, and political decision-making. This emphasises the importance of understanding these trends to guide R&D and innovation activities within the alliance, including capability planning. This report summarises the future landscape of military technologies, considering their increasing intelligence, interconnectedness, decentralisation, and digital nature, which will lead to autonomous, networked, multidomain, and precise military capabilities. It also highlights the dual-use nature of these technologies, which are developed principally in the commercial sector, and the need for NATO to adapt to this dynamic technological evolution to maintain operational effectiveness. The document lists several EDTs that are expected to impact NATO's strategic and operational capabilities: (i) AI, (ii) Robotics and Autonomous Systems, (iii) Biotechnology and Human Enhancement, (iv) Big Data and Information Communication Technologies, (v) Electronics and Electromagnetics (new supplemental EDT), (vi) Energy and Propulsion, (vii) Hypersonic Technologies, (viii) Novel Materials and Advanced Manufacturing, (ix) Quantum Technologies and (x) Space Technologies.

Although NATO has always considered the critical consequences of technological advancements, its focus on EDTs[9] and other vital areas has increased relatively late. This has led to the need for a dynamic acceleration of advanced technology development and broader stimulation of this sector, which initiated the establishment of the NATO Innovation Fund and the Defense Innovation Accelerator for the North Atlantic (DIANA) in 2021. What led to the intensified effort in collaborative exercise organisations, research activities, and infrastructure investments reflects NATO's cohesive approach to common technology advancement, awareness of the need for responsible development, ethical and interoperability issues, and a unified strategic vision for collective defence and security.

3. Key technology areas and their impact on operational effectiveness and other domains

Based on analyses of the operational needs and recognition of the critical technologies seriously impacting the future operational environment by NATO, EDA, the U.S., and China (supported by Rear Admiral (LH) (Ret.) Cem Okyay[10]), a list of technological areas with serious potential for civilian exploitation (dual-use effect) was identified and further described (most fell under the approved list of "emerging and disruptive technologies" within world-advanced armies).

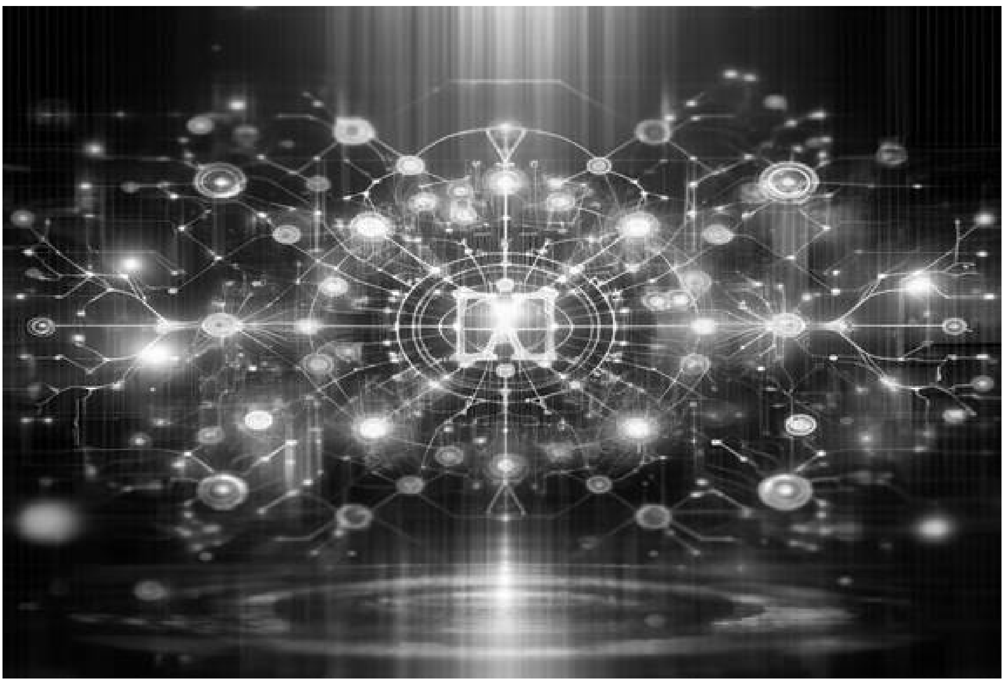
3.1. Artificial intelligence and machine learning

AI and machine learning are not just technological advancements, but have revolutionised paradigms across various domains.[11] These technologies offer transformative capabilities in the domain of operational effectiveness.[12] From predictive maintenance (which forecasts equipment failures before they occur) to advanced data analytics in finance (detecting fraudulent activities in real-time), efficiency

9 NATO EDT's, 2024.
10 Okyay, 2023.
11 Suárez and Baeza, 2023.
12 Johnson, 2023.

enhancement is decisive. Numerous civilian fields have extensively adopted AI. AI-driven diagnostic tools enable early disease detection in the healthcare and logistics fields and machine learning algorithms optimise delivery routes and save time and resources. Moreover, in the defence sector, AI systems enhance surveillance capabilities, process vast streams of intelligent data, and assist or drive autonomous decision-making for drones and other vehicles. These applications have a significant civilian overlap. However, the integration of AI and ML also introduces ethical and security challenges, especially when decisions previously made by humans are delegated to machines. Thus, the pragmatic aspects and influence of AI and ML, while offering unprecedented advantages, call for a balanced approach to harness their potential responsibly and sustainably. AI/ML presents a decisive opportunity for future battlefield dominance,[13] and a nation that has made reasonable progress in this field may quickly acquire the operational and strategic capabilities required to dominate the world. As an example of the visual "creativity" (until recently, an exclusively human domain) of AI, see Figure 2. "How AI sees AI".

Figure 2: How AI sees AI (generated by DALLE.-E in approx. 10 seconds.)



13 Scharre, 2023, pp. 293–299.

3.2. Autonomous systems and robotics

Autonomous systems and robotics represent the convergence of technology and functionality, drastically redefining the operational landscapes across numerous domains.[14] Robots maintain consistently high production standards, unaffected by fatigue or distraction, resulting in heightened efficiency and reduced errors. These systems have also penetrated challenging terrains, from space and the deep sea to autonomous vehicles, promising to transform urban transportation. In the industrial and agricultural sectors, drones autonomously map vast areas and carry various sensors and loads. In the medical domain, robot-assisted surgery outperforms humans in terms of precision and stability. In defence and security, unmanned aerial and ground vehicles are becoming force multipliers, enhancing surveillance and reducing risks to humans. However, as these autonomous systems gain prevalence, they also become a central point of debate regarding job displacement, ethical concerns in decision-making,[15] and potential misuse. The trajectory of autonomous systems and robotics implementation emphasises the importance of adapting and responsibly integrating these tools into society.

3.3. Space technology

Space technology has evolved into a crucial asset underpinning military functions and operational effectiveness. Satellite networks orbiting the Earth have become the focus of modern militaries, providing critical information ranging from precise geolocation data to detailed meteorological insights. These capabilities enhance navigation, surveillance, and communication systems, ensuring that military operations are coordinated accurately and reliably. Space technology also encapsulates the development of missile defence systems, which are essential for national security in developed countries.[16] Furthermore, space assets facilitate a global range of military communications, enabling real-time coordination and strategic decision-making across vast distances. However, this dependency on space technologies necessitates the evolution of new doctrines and defence strategies to protect this strategically crucial extra-terrestrial asset from potential adversaries and emerging threats.

3.4. Quantum technologies

Quantum technologies, rooted in the principles of quantum mechanics, are poised to introduce significant shifts in military operational effectiveness and domains.[17] For instance, quantum encryption promises virtually impenetrable communication

14 Mazal et al., 2019, pp. 53–80.
15 De Mattia, 2022.
16 Manson, 2020.
17 Krelina, 2021.

networks, thereby ensuring the confidentiality and security of critical information. Quantum sensors, which leverage the hypersensitive nature of quantum states, can detect stealth aircraft or submarines with unparalleled precision, negating the traditional concealing advantages. Furthermore, developing a practical quantum computer could revolutionise data processing and analysis, enabling the decryption of previously impervious coded messages and drastically enhancing intelligent operations. Simultaneously, this computational performance can redefine warfare simulations with unprecedented accuracy. However, establishing these quantum capabilities also introduces new challenges. For instance, the race to secure quantum supremacy could destabilise existing power dynamics, and the need to defend against quantum-based threats will demand novel defence strategies. In essence, quantum technologies are not merely tools, but game-changers set to redefine the military strategy and operations landscape.[18]

3.5. Hypersonic weapons

Hypersonic technology marks a transformative development in modern warfare, significantly influencing operational effectiveness in various military domains.[19] Hypersonic aircraft and missiles, exceeding the speed of Mach 5, offer unprecedented operational performance and agility, providing a strategic advantage within immediate response and strike capabilities. High velocity and high-altitude manoeuvrability make hypersonic systems challenging for current missile defence systems.[20] This dramatically shortens decision-making timelines and seriously complicates defensive strategies, potentially necessitating a re-evaluation of existing missile defence doctrines. Furthermore, the dual capability of some hypersonic systems capable of delivering both conventional and nuclear payloads adds a layer of strategic complexity, impacting deterrence dynamics and global security. Advances in hypersonic technology not only enhance operational effectiveness in terms of speed and precision but also significantly influence strategic military planning and international security discourse. The civilian domain (except security aspects) could benefit from this technology in various areas such as space and aerodynamics, for instance, the development of next-generation commercial aircraft that can reach supersonic or hypersonic speeds.

3.6. Internet of Things (IoT)

A vast network of interconnected devices and systems characterises the IoT. It has enormous potential in the military sector for supporting extended operational

18 Scharre, 2023, pp. 37, 39.
19 Cone, 2019.
20 Volkov, 2023.

capabilities and flexibility.[21] Through IoT, assets (ranging from wearable sensors to large-scale military hardware) can seamlessly share real-time data and achieve enhanced situational awareness, thereby improving decision-making accuracy. On the battlefield, IoT-enhanced surveillance systems can detect and transmit threats instantaneously and allow predictive analysis to identify potential critical states or configurations, equipment failures, and vulnerabilities. However, this vast network[22] presents new challenges (such as an increased surface area for potential cyberattacks) that require robust cybersecurity measures to protect the integrity of IoT ecosystems, as such technologies promise a significant shift in military efficiency. IoT in the civilian domain has numerous benefits. One of the main advantages is the considerable enhancement in the efficiency and convenience of everyday life. This improvement is achieved through automation and optimisation of routine tasks, leading to increased productivity, energy savings, and improved quality of life in areas such as smart homes, security and safety, wearable health devices, smart cities, smart grids, climate and environmental monitoring, precision farming, intelligent transportation systems, energy management, and efficiency.

3.7. 5/6G and communication technologies

The emergence of 5G and anticipation of 6G communication technologies have led to significant progress in military operational effectiveness and strategy.[23] These advanced communication infrastructures promise unprecedented data transmission speeds and ultra-reliable low latency, which are critical factors in real-time decision-making and coordination on modern battlefields.[24] For autonomous military assets, such as drones and ground vehicles, these enhanced communication networks enable interoperable communication, fast data sharing, and integration into larger systems. An enhanced bandwidth of 5/6G can support the simultaneous deployment of multiple sensors (from wearable devices for soldiers to advanced radars), allowing for comprehensive situational awareness on battlefields. However, these advances have been challenging. Reliance on high-frequency bands makes the infrastructure more susceptible to interference, requires a denser deployment of relay nodes, and amplifies the risk of cyber threats and electronic warfare tactics disrupting these advanced communication systems. While 5/6G technologies promise to revolutionise military operations and strategic domains, their operational adoption must be accompanied by robust defence mechanisms to protect and optimise their potential, contrary to the civilian domain, where no significant electronic warfare interception is anticipated. The main benefits of 5G and emerging 6G technologies in the civilian domain are that they are compatible with the military; thus, they are a dramatic

21 Manso, 2023.
22 Dahdal et al., 2023.
23 Salor and Baeza, 2023.
24 Ahokangas and Aagaard, 2024.

improvement in connectivity, a critical enabler for remote (real-time) control and complex interactions, supporting economic growth and innovation, public safety, remote work, and education.

3.8. Cloud computing

With its centralised data storage and processing capabilities, cloud computing has become increasingly essential for modern military operations.[25] This technology enables the efficient aggregation, analysis, and dissemination of vast datasets, enabling militaries to achieve enhanced situational awareness and faster decision-making, instead of relying on different and localised databases. Forces across land, air, sea, and cyber domains can access and contribute to a unified information pool, high-performance computing hardware (HW), and centralised software (SW) services, ensuring compatibility across various devices, coordination, and synergy within military operations. For instance, training simulations, computer-assisted exercises[26] (CAX), military logistics, and staff administrative tasks can be easily optimised and coordinated, offering scalable solutions adaptable to a particular operational demand. However, data centralisation poses security concerns because potential cyberattacks on these cloud infrastructures can compromise vast collections of sensitive information. The primary advantage of cloud computing for civilian and military applications is its notable improvement in the accessibility and scalability of computer resources and services. This technology allows individuals and organisations to access vast computing resources, data storage, and various applications and services over the Internet without substantial investment in physical hardware. The main benefits include accessibility, flexibility, on-demand resources, cost-effectiveness, rapid deployment, quick updates or innovation, enhanced data management, easy collaboration, reliable infrastructure, security enhancements, overall energy efficiency, and sustainability.

3.9. Biotechnology and human augmentation

Biotechnology and human augmentation converge to redraw the boundaries of what is possible in the military, pushing human capabilities and resilience to another level.[27] Advances in biotechnology offer solutions, such as rapid wound healing, enhanced resistance to physical and psychological stress, and the potential to operate in extreme environments with minimal protective equipment. Human augmentation, from exoskeletons and augmented senses (beyond standard human

25 Blakley et al., 2022.

26 Computer assisted exercises use a real time computer simulated operational environment for improving staff readiness in operations, and military decision making. They are recognized for their cost efficiency and effectiveness in reducing risk while facilitating multinational participation from different locations.

27 Hutcheon, 2021.

capabilities) to neural interfaces, enhances the operational efficiency of soldiers and extends mission endurance. These advances also introduce ethical dilemmas, potential vulnerabilities, and questions regarding the long-term impact of augmented personnel. Moreover, closer biotech integration increases the risk of cyberphysical attacks, potentially becoming a new dimension of warfare. Although biotechnology and human augmentation have immense potential to redefine military effectiveness, they have serious ethical, strategic, and security implications that must be resolved in advance. These fields are at the forefront of medical developments in the civilian domain. Thus, these technologies have the potential to dramatically improve the quality of life, extend lifetime, and increase human performance, impacting the fields of medical breakthroughs and therapeutics, disease treatment and prevention, regenerative medicine, prosthetics and implants, sensory and cognitive enhancement, genomic medicine, diagnostic tools, and ageing research.

3.10. Cybersecurity and cyber resilience

In an age when the cyber domain is as critical as the physical domain, cybersecurity and cyber resilience have emerged as essential components of military operational effectiveness.[28] As modern armies integrate sophisticated technologies, from drones and AI-driven intelligence systems to advanced communication networks, their dependency on cyber infrastructure has increased exponentially. Despite offering unprecedented operational benefits, the cyber domain is a domain for cyber warfare and is susceptible to hostile operations by adversaries, namely, cyberattacks.[29] Cybersecurity is both a technical requirement and a strategic imperative. Beyond defence, cyber resilience (the ability to anticipate, withstand, recover from, and adapt to adverse cyber events) is crucial, as it ensures that military operations can continue despite cyber adversities and adapt rapidly to evolving threats. Integrating cybersecurity and cyber resilience enhances military capabilities, shifts doctrines from old-fashioned offences, and defends against robust digital protection and adaptive recovery. This new paradigm upgrades modern military operations, encompassing battles in physical and virtual (cyber) domains. The military domain, like others, has a significant interconnection with its civilian counterpart, and in some cases, these domains share particular hardware and software resources and physical infrastructure. The primary aim of cybersecurity and resilience in the civilian domain is the comprehensive protection of the digital ecosystem, ensuring the security of personal information, continuity of critical services, and the overall trust and reliability of the digital infrastructure. These technologies and principles are crucial to the functioning of the modern world and are thus extremely important.

28 Hallaq, 2017.
29 Salomon, 2022.

3.11. Big data analytics

In today's digital era, militaries are overwhelmed by the vast amounts of data linked to the Common Operations Picture (COP) update and processing. Big data analytics emerged as a critical tool[30] for transforming data flows into actionable intelligence and strategic insights. The employment of advanced algorithms and computational hardware enables patterns to be uncovered, highlighting anomalies, anticipating adversarial steps, optimising resource allocation, ensuring the timely and efficient deployment of assets, and making informed and prompt decisions.[31] Beyond operational efficiency, big data analytics provide a strategic vantage point, enabling militaries to understand geopolitical trends, predict potential conflict zones, and adapt strategies accordingly. However, data-driven decision-making introduces serious challenges, such as dependency on accurate and valid data, complex validation, and algorithmic-based vulnerabilities (necessitating particular oversight). The Big Data approach is expanding, even in the civilian domain, providing deep insights into complex datasets for optimal decisions, and improving personalisation, operational efficiency, public services, healthcare, financial stability, environmental sustainability, and education. Experience from practice and reciprocal evolution would be beneficial to both domains.

3.12. Advanced materials and manufacturing

Progress in advanced materials and manufacturing involves the transformation of military capabilities in various areas, primarily combat resistance, logistics, and sustainment.[32] Dynamic evolution in material science (such as super-lightweight composites and unique metamaterials absorbing or shaping electromagnetic waves) has enabled the development of advanced military equipment or assets. Similarly, advanced manufacturing techniques, such as additive manufacturing or 3D printing, offer flexible and rapid production of complex components.[33] This allows parts to be manufactured in remote locations, even on battlefields. This capability accelerates repair and maintenance and reduces the logistical burden of transporting unnecessary spare parts.[34] Additionally, integrating intelligent materials with unique attributes such as self-repair, self-shaping, and environmental adaptation promises to extend the lifetime, adaptability, and maturity of military assets. These advancements have dramatically enhanced military operational effectiveness and introduced new challenges and responsibilities. This field significantly overlaps with the civilian domain, in which the main benefits of advanced materials and manufacturing are

30 Govindaraju, Raghavan and Rao, 2015, pp. 260–262.
31 Ravi, 2021.
32 NATO EDT's, 2024.
33 Mamalis, 2019.
34 Hahn, 2019.

apparent, grounded in enhancing product performance and sustainability. Examples of advanced materials include carbon-fibre composites, graphene, shape-memory alloys, self-healing metals, polymers and elastomers, fullerenes, carbon nanotubes, nanocrystals, biodegradable polymers, and superconductors. However, as these advanced materials and manufacturing techniques become more prevalent, they also require new training, maintenance, and manipulation standards and considerations regarding recyclability, environmental impact, and other issues.

3.13. Energy and propulsion

Developing advanced energy and propulsion technologies is crucial for enhancing the operational effectiveness in all military domains. Advancements in this field, include, for instance, new generations of engines, energy storage (batteries), alternative fuels, and innovative propulsion methods,[35] which could dramatically expand the performance of all military assets with prolonged endurance, safety, higher speed, and payload, thus enhancing operational superiority and strategic reach. The potential of dual-use energy and propulsion technologies in the civilian domain is apparent; however, these areas do not always converge because their principal objectives differ (operational effectiveness vs. environmental and economic factors). The main benefits include a significant increase in energy efficiency, cost reduction, and a potential transition towards cleaner and sustainable energy sources, which supports the urgent need to reduce greenhouse gas emissions and slow global climate change. Examples of energy and propulsion technology with dual-use potential include nuclear fusion, propulsion and microreactors, electric and hybrid-electric propulsion systems, directed energy transmission technology (lasers[36] and high power microwaves), hypersonic propulsion, power based on changes in buoyancy, solar photovoltaics and concentrated solar power, advancements in battery technology[37] such as solid-state batteries, development of ultra-fast charging and wireless charging technology, hydrogen fuel cells, energy smart grids and microgrids, advanced biofuels, and space-based solar power.

3.14. Directed energy weapons

Directed Energy Weapons (DEWs), which include systems based on laser and high power microwave technology, are likely to significantly improve operational effectiveness.[38] This is supported by critical advantages that allow them to outperform contemporary systems or approaches. These benefits arise from extreme precision and speed-of-light engagement, which provide revolutionary tactical advantages in

35 Guillaume et al., 2019.
36 Rezunkov, 2021.
37 Wasim et al., 2022.
38 U.S. DOD, 2023.

all scenarios and activities. Tactical experience shows that the capabilities of DEWs can be effectively applied to high-speed and small targets such as incoming artillery shells, small drones, and rocket barrages, which present a game changer in tactics and situations that obsolete technology cannot manage.[39] Moreover, DEWs have a low cost per shot compared with conventional munitions, offering economic efficiency in prolonged engagements. Their almost unlimited magazine capacity ensures sustained operation in extended conflicts, as long as power is available.

The operational effectiveness of DEWs is also apparent in their stealth characteristics. These weapons produce minimal exposing effects (sound and visible signatures), rendering them hard to detect and trace back. Furthermore, the adaptability of DEWs to various platforms, from handheld devices to naval ships and aircraft, demonstrates their versatility in various military fields. While DEWs are primarily associated with military applications, the primary technologies and principles of directed energy have significant potential benefits in various civilian sectors, such as material processing, additive manufacturing, optical communications, power transmission, wildlife protection, vegetation control, laser surgery and therapy, non-lethal crowd control, search and rescue operations, remote sensing, material science, and indirect material diagnostics.

3.15. Adaptive education and training

Adaptive education and training technology[40] are critical components for future military training and improving human operational effectiveness. This technology employs an advanced conceptual framework of high-fidelity simulations, virtual reality VR- and AI-driven learning platforms to create personalised and immersive training programmes for individuals to achieve optimal learning.

By leveraging these technologies, military training has become more intensive, engaging, and realistic, focusing on the areas of knowledge and skills that require improvement. Adaptive training technologies also allow new information and tactics updates to be quickly disseminated across the armed forces, ensuring that military personnel stay up-to-date with the latest trends and operational developments. Moreover, these technologies contribute to cost-effectiveness by reducing the physical infrastructure or resources needed and enabling the simultaneous training of large numbers of personnel. The benefits of adaptive education and training in the civilian domain highly overlap with those in the military, and technological advancement in both domains can contribute to improvements in the civilian education.

39 Del Monte, 2021.
40 Durlach, 2012.

3.16. Blockchain technology

Blockchain technology, often associated with cryptocurrencies, has found innovative potential within the military, promising enhanced security, transparency, and administrative simplicity.[41] A blockchain is a decentralised register that ensures data integrity through cryptography, making unauthorised alterations extremely difficult. In the military, blockchain can authenticate supply chains, providing information on the origin and quality of equipment. The communication system offers a tamper-proof record for intelligence operations, ensuring the authenticity and integrity of critical information exchanged. Moreover, blockchain can ensure transparency and traceability in complex defence contracts and procurement networks, thereby reducing bureaucratic issues and potential corruption. This technology also has possible implications for secure voting systems for deployed troops and transparent personnel authentication. However, as with any technological integration, there are some challenges to consider. The scalability and energy consumption of blockchain solutions, especially in large-scale applications, require optimisation, and although blockchain holds significant promise for modernising various military domains, its integration requires careful consideration and adaptation. In the civilian domain, blockchain technology already supports cryptocurrencies such as Bitcoin, Ethereum, Ripple, and Litecoin, but its applications extend far beyond digital currencies.[42] It has been adopted in various sectors, including finance, supply chain management, healthcare, and identity verification, owing to its potential to provide secure and transparent solutions to many complex problems involving trust and transaction verification.

3.17. Electronics and electromagnetics

Integrating advanced electronic systems and electromagnetic technologies into the military could dramatically increase situational awareness, real-time decision-making, precision targeting, secure communication, stealth capability, manoeuvrability, and other areas, thereby amplifying the efficiency and strategic capabilities of the armed forces. The miniaturisation and performance increase of electronics and electronic warfare[43] capabilities towards smaller, lighter, multipurpose, flexible, and energy-efficient devices has enabled the deployment of advanced and game-changing systems, such as micro-drones, nano-robots, micro-radars, EW interceptors, jammers, spectral analysers, wearable bio-integrated electronics, human-augmented devices, next-generation surveillance equipment.. Such technology is characterised by quality and performance, which could drastically outperform an obsolete asset

41 Bikos and Kumar, 2022.
42 Krichen et al., 2022.
43 *Electromagnetic warfare*, 2023. [Online]. Available at: https://www.nato.int/cps/en/natohq/topics_80906.htm (Accessed: 12 January 2024).

and tactical approaches on the future battlefield, applied in an offensive or defensive/protective manner. For example, the latest research demonstrates the revolutionary potential of plasma shields to high power microwaves, seriously impacting anti-drone warfare.[44] The dual-use nature of these technologies is significant and omnipresent within our everyday lives, extending the civilian domain of advanced electronics and communications we rely on. Any advancement in this field will immediately affect both domains.

3.18. Brief summary

The current era of military development is characterised by a mosaic of technological advancements in many areas. These changes are not just minor improvements but are transformative forces that redefine operational effectiveness and strategy. They provide military precision, speed, and adaptability, enabling more nuanced and informed real-time decision-making. However, these advances have resulted in new vulnerabilities and ethical considerations. As the boundaries between the digital, physical, and biological domains become increasingly unclear, a comprehensive defence approach that integrates advanced tools, robust countermeasures, continuous training, and ethical frameworks is required. The future of military operations, shaped by this technological renaissance, offers unimaginable opportunities and significant challenges requiring a balance between innovation, responsibility, and anticipation.

These areas exhibit substantial overlap and dynamic evolution. Any additional motivated acceleration could lead to the achievement of specific milestones and revolutionary progress in these areas sooner or later, benefiting society. Although opinions differ, an escalation of the armament race and development does not generally align with the philosophical values of modern society. However, the contemporary world is not uniform in this regard, as the history of humankind shows that conflict has been deeply rooted in human nature and shaped by our survival instincts since ancient times. This will significantly affect current and future security environments, and effective strategies to address these issues are needed.

4. Main aspects of military advanced technology within future warfare

The future battlefield is anticipated to differ vastly from traditional combat zones shaped by rapid technological advancements and changing geopolitical dynamics. Based on contemporary trends and estimations, integration of a vast number of

44 Impact Lab, 2024.

advanced technology components is expected, with a critical dependency on the cyber domain and a severe impact on other areas, such as information warfare and psychological operations. These factors will lead to a dynamic and complex environment in which the future landscape of threats is also expected to transform considerably with the rise of non-state entities and the prevalence of asymmetric warfare. The probability of global conflict has risen with the evolution of the world security environment. This shift demands that military strategies should be flexible, integrate diverse advanced technologies, enhance cyber capabilities, and employ innovative and unconventional approaches to counter the complex challenges of these conflicts.

4.1. Performance-oriented battlefield – the result of a fundamentally pragmatic approach

The logical assumption, derived from industrial domains and trends, is that future battlefield evolution will be driven by a highly pragmatic approach, leading to cost/benefit optimisation, which will inevitably discriminate against some redundant military approaches and dogmas. The critical reasons for contemporary changes or transition to a highly technological battlefield are the level of maturity of operationally proven or effective advanced military technology and its expected dynamic evolvement (proven by experience and supporting trust in the future technology operational performance). This has led to a reconsideration of contemporary approaches and focused attention on future military development strategies. One of the critical aspects of this activity is the evaluation of the perspectives of human (as a centric entity around military operations or activities) performance versus advanced technology in the short- and mid-term vision. This is coupled with complex considerations regarding the cost-effectiveness and physical limitations of technological and biological systems.[45] The main limitation is human reaction time and the speed of action, which are critical not only for close combat activities but will be decisive for operational reasoning in the future.

From an operational perspective, it seems that the centre of gravity is an open and independent focus on the critical objectives of the military effort, which have not changed significantly over the centuries, such as threat elimination, occupying territory, conquering areas, and defending a sector. If we abandon the need to maintain certain (usually old-fashioned) dogmas in orientation towards achieving these goals, which typically complicate[46] the effective approach to the solution, we open up space for mathematical modelling of these activities and subsequently

45 While the “production and training” of human soldiers could take several decades, the manufacturing of technical systems could take minutes or seconds.

46 These complications could arise from dogmas like: ‘the commanders experience and intuition are the backbone of his decision-making process, ‘only the human decision will be accepted for execution’, ‘combat formations will follow only the approved doctrinal rules’, ‘territory could be considered as a conquered only when the foot of the friendly soldier touch it’.

advance automation and optimisation of operational multi-criteria processes leading to the selected goals. This is a crucial conceptual and philosophical transition process for military systems based on pure pragmatism, leading to a future performance orientation that seems dynamic and unpredictable, especially from a mid-to-long-term perspective. This is because there is a lack of adequate options for regulating this process in the contemporary world. Even so, we might pinpoint crucial components or areas that have pivotal or central functions and experience notable changes such as automation of combat and decision-making activities, logistics and supply chain efficiency, adaptive training and education strategies, cost-effective solutions and flexible, "on-demand" serial production automation, resilience and rapid development of countermeasures, international collaboration and partnerships, and biotechnology and bio-augmentation.

As most of these areas have a serious overlap with the civilian domain, there is a strong assumption that (in our globalised world) progress in the military domain will quickly affect another domain and vice versa. The direction of innovation flow usually reflects the amount of investment and the attention paid to a particular area. Based on the global deterrence and increases in defence budgets, there is a logical expectation of a dynamic military innovation pace we have never experienced before, backed by advanced technologies and an extraordinary military performance orientation we remember from the Cold War. From a logical and pragmatic point of view, we could expect a broader and more intensive hybridisation of future warfare and an extension of the battlefield to more expansive areas of states and neighbouring countries. From a philosophical perspective, there are parallels between the military and civilian domains grounded in the principles of Industry 4/5.0, driven by the particular performance aspects pursued.

4.2. Transition to an AI Command-and-Control in future military operations

Based on previous and contemporary operational experiences and the evolution of modern warfare, there is a solid and logical assumption that the future battlefield will require a new concept of the command-and-control[47] (C2) approach at all levels of command.[48] The initial idea of this transition was introduced in the Defense Advanced Research Projects Agency (DARPA) "Deep Green"[49] project in 2008. This comes with a fundamental shift in the so-called OODA (observe, orient, decide, act) loop[50] paradigm in the context of the expected increase in battlefield dynamics

47 Command and Control (C2) in a military context refers to the exercise of authority and direction by a designated commander over assigned and attached forces in the accomplishment of a mission. It is a fundamental concept in military operations, playing a crucial role in organizing, directing, and coordinating military activities.

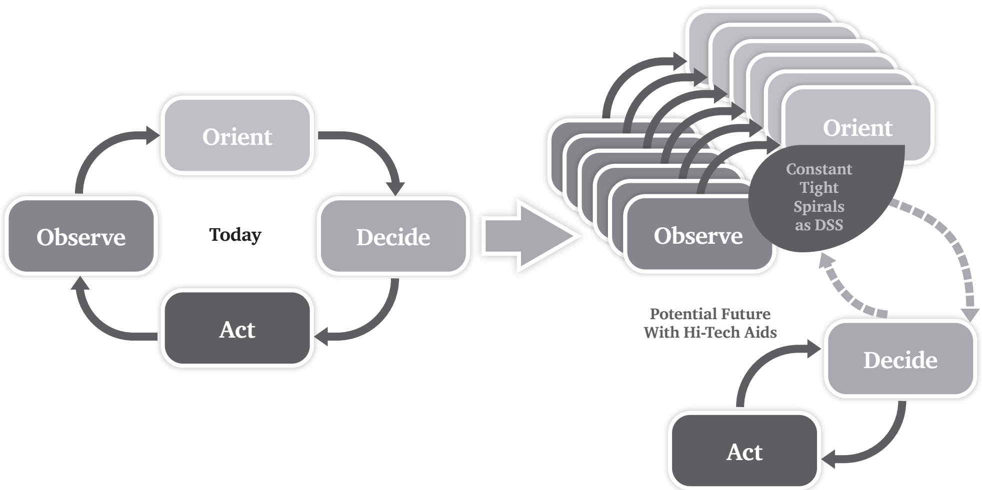
48 Sarcia and Colo, 2023.

49 Surdu and Kittka, 2008, pp. 4–12.

50 Originally formulated by military strategist John Boyd, the OODA loop was initially a sequential process. Each phase followed the other linearly: observe, orient, decide, and act.

(arising from a logical assumption of the reduction in reaction/response times and the enormous growth of tactical entities on the battlefield). In this highly complex operational environment, obsolete C2 (management) principles and approaches are no longer effective.[51] While the systematic, original OODA serial approach often resulted in delayed responses, it was a disadvantage in high-tempo combat environments, where the expected operational dynamics increased up to a level that caused the old-fashioned reactive approaches to no longer be effective. Due to the reactions practically settling in place, the situation usually varies significantly from when the particular Course of Action (COA[52]) is planned. The original "Deep Green" OODA upgrade forecast, becoming an indisputable fact today and remaining critical for the future, requires serious changes in the military concept of decision-making processes, and the traditional serial OODA loop must be parallelised.

Figure 3: Graph of the serial OODA paradigm transition to the parallelised version



The parallel OODA loop paradigm revolutionises the deeply rooted military decision approach and incorporates simultaneous actions across different phases. This approach significantly accelerates decision-making and injects a level of dynamism and flexibility previously unreachable in the serial model. It also promotes a more decentralised command hierarchy, empowering lower levels of command

51 Black, 2024.

52 Course of Action (COA) refers to a plan or method proposed and developed to achieve a specific mission or task. It outlines how available resources (such as troops, weapons, equipment, and time) can be used to deal with a specific situation or to accomplish a particular objective. The development and analysis of COAs are integral parts of the military planning process.

with autonomy to react swiftly, informed by real-time data, and a comprehensive understanding of the broader battlefield context and higher echelon commanders' intentions. Incorporating advanced technologies, such as high-fidelity wargaming[53] constructive simulations,[54] AI,[55] and integrated communication networks, further amplifies the capabilities of the parallel OODA loop. These OODA upgrades facilitate rapid information processing and sharing, enabling cohesive and synchronised actions among military forces, which are pivotal for ensuring quick, strategically coherent, and contextually relevant combat responses. This fact, backed by the evolution of modern computing technology, will inevitably result in a transition to an AI-enhanced C2 system in future military operations. The key factors for a successful transition of current C2 to AI-aided/driven C2 and its potential dual-use aspects are understanding the fundamental role of C2 in the military, the role of automation in C2 systems (C5ISTAR),[56] increased confidence in using cutting-edge technologies, improving situational awareness, autonomy, and warfare automation (within C2), and international cooperation.

4.2.1. The role of C2 in the military

C2 creates a fundamental framework within military operation management and is integral to orchestrating the use of military forces during warfare. The C2 philosophy enables military commanders to plan, direct, and control forces to accomplish assigned tasks. C2, supported by the military decision-making process (MDMP),[57] involves gathering and processing information, making decisions, executing them, and monitoring outcomes, emphasising flexibility and responsiveness during military engagements. A practical C2 framework emphasises the establishment of a transparent command hierarchy, resilience of communication networks, and optimisation of decision-making processes. Real-time information exchange is pivotal for commanders to evaluate the operational state of a battlefield accurately, seek and coordinate effective COAs, and disseminate commands. Thus, the efficiency of the

53 Wargaming in the military context is a decision-making tool that simulates conflict scenarios or battles to test strategies, develop and evaluate courses of action, and predict their outcomes without actual combat. This practice allows military leaders and planners to anticipate potential challenges and outcomes in a controlled, risk-free environment.

54 Constructive simulation in the military context is used primarily for training, analysis, and decision support. It involves the creation of a virtual environment where hypothetical scenarios are played out, often for the purposes of training, strategy development, or decision-making analysis.

55 Tarraf, 2022.

56 C5ISTAR is an acronym representing a broad set of functions and capabilities in modern military operations. It stands for Command, Control, Communications, Computers, Cyber (C5), Intelligence, Surveillance, Target Acquisition, and Reconnaissance (ISTAR). This framework encompasses a number of activities and technologies fundamental to military operations.

57 The military decision-making process (MDMP) is a detailed, step-by-step process used by military commanders and their staff to develop and plan military operations. It provides a structured framework for analysing a situation, developing options, and deciding on the best course of action.

C2 framework is critical for maintaining the tempo of operations and ensuring that military responses are coherent and aligned in real-time with opponents' reactions. With technological advances, C2 evolved to incorporate network-centric operations that leverage information superiority and collaborative engagement to achieve strategic advantages. Modern C2 systems aim to seamlessly integrate intelligence, surveillance, reconnaissance, and operational planning to empower decision-makers at all levels, creating the so-called C5ISTAR systems (pushing C2 theory to an advanced technological framework).

Although C2 is connected to the military, philosophically, C2 and the civilian domain closely overlap within the management field. Thus, any theoretical upgrades to the C2 conceptual framework could be reflected in the dual-use aspects that are already present, mainly in security areas (level of command, hierarchy, responsibility delegation, etc.).

4.2.2. C5ISTAR systems

The military term C5ISTAR covers various technologically advanced components and processes that are essential to modern warfare and military operations. This concept represents the high-level integration of systems and activities that the armed forces utilise to secure and maintain information superiority in operations through real-time analysis of the COP[58] The historical roots of these systems can be traced back to the development of telegraphy and radio in the 19th century. These technologies have enabled militaries to communicate over long distances, leading to critical breakthroughs in the art of warfare. These systems have continued to develop with an extremely high degree of technical integration and complexity. These systems collect and process information from numerous sources, including remote sensors, satellites, automated drones, robots, and social media. There are many emerging trends in C5ISTAR technology in the prognosis and estimations of the future battlefield, which raises many concerns and requirements, such as real-time advanced processing of an enormous amount of battlefield data generated every second (the amount of data is expected to increase exponentially in the future with an increased number of next-generation sensors and system deployments). This has led to several outcomes, the major one being the application of AI (with a focus on ML) to automate tasks and improve decision-making. Another trend is the development of cloud-based C5ISTAR systems, which can provide global access to information and resources. As mentioned, C5ISTAR systems are essential to modern warfare because they provide militaries with the information and tools they need to succeed on the battlefield. Nonetheless, a conceptual similarity exists between several civilian management systems across numerous fields, from industry to security and government.

58 A common operations picture (COP) is a single, identical display of relevant operational information that is shared by more than one command. It is a critical tool for situational awareness and decision-making in military operations.

4.2.3. Building trust in advanced technology

Trust in military technology is essential for the success of defence operations and is achieved through rigorous operational testing and validation (OT&V). OT&V is the empirical backbone that ensures that new technologies perform as required under the broadest spectrum of battlefield conditions. The process of OT&V encompasses a systematic evaluation from the early developmental stages to field trials and post-deployment assessments, encapsulating the effectiveness and survivability of technological solutions in operational settings.

To the greatest extent possible, OT&V processes must be transparent and comprehensive, including scenarios that reflect current and anticipated mission challenges (cyber threats, electronic warfare, extreme physical environments, and countermeasures). The results of these tests are fed back into the development loop to improve the design, tactics, training, and maintenance protocols. OT&V also facilitates user familiarisation, an often-overlooked factor that is critical to the successful adoption of new military technologies. Moreover, trust is established by demonstrating the technology's adherence to ethical standards and rules of engagement, ensuring that it aligns with legal and moral constraints under the laws of war. This aspect of trust is fundamental, as technological advancements, such as AI and autonomous systems, present new ethical dimensions for warfare.

OT&V is an indispensable part of the defence technology lifecycle. It underwrites the functionality and safety of new systems and cultivates the trust and confidence of war fighters who rely on these systems, thereby ensuring that the human element remains at the heart of technological advancement in military operations. The military sector is usually highly conservative, and building trust in new and revolutionary technologies takes time. Any mistake or technology failure can result in serious latency extensions or technology rejection. This area resembles many civilian fields where trust depends on positive experiences linked with reliability and performance, which are critical, such as autonomous transportation, the aircraft industry, the IT sector, and cybersecurity. Specific improvements in this area could potentially be used in the civilian domain.

4.2.4. Improved situational awareness

Improved situational awareness is crucial for operational efficiency and domination within the information domain. As decision-making processes become more complex and are supported by a fusion of real-time intelligence, long-range surveillance, and data-driven insights, potential options become vast, requiring additional processing and an enhanced understanding of battlefield relationships. This element becomes much more significant when we add a temporal dimension to the battlefield's state space, which is required to identify potential future crucial configurations.

This highly complex and multidimensional mathematical model of the battlefield must be processed in real-time using cutting-edge computational algorithms and supercomputers to extract extensive datasets to identify patterns and trends, exposing the concealed operations of adversaries and signalling emerging threats. The prompt analysis of such data allows military commanders to make rational decisions with unprecedented accuracy and preventive judgements. Although much work has been done on AI implementation within tactical scenario analyses and planning,[59] the complexity of the contemporary battlefield introduces many challenges and reveals gaps, which are areas of current and future research linked to quantum computers and advanced AI technology, and have become one of the central fields of technological competition in the military.[60] All modern armies are searching for comprehensive situational awareness technology that enables a more agile and precise allocation of resources, timely responses to emerging threats, and more coordinated manoeuvres, ultimately leading to superior tactical and strategic outcomes.

4.2.5. The role of autonomy and warfare automation in C2

Autonomy and automation will inevitably play transformative roles in future military operations, reshaping strategies and tactics across various domains and must be integrated within the C2 area. Integrating autonomous systems will enable militaries to execute complex missions with greater efficiency and reduced risk to human personnel. However, this opens up an additional dimension of challenges and problems the military has never previously faced. The main problem lies in effectively managing a potentially extreme number of these entities in the future, especially within a communication-restricted environment. This challenge leads to the pursuit of hybrid or distributed architectures and complete autonomy in particular areas of defence technologies.

As these technologies advance, they will augment existing capabilities and create new operational paradigms where human-machine relations become essential for achieving strategic objectives. However, this shift requires careful consideration of the ethical, legal, and operational implications, ensuring that the integration of autonomy and automation aligns with established military values and objectives. Nevertheless, the comprehensive automation of military components, assets, and the C2

59 NATO STO SAS-139. [Online]. Available at: https://www.sto.nato.int/publications/STO%20Technical%20Reports/STO-TR-SAS-139/$$TR-SAS-139-ALL.pdf (Accessed: 15 January 2024); SAS-150, SAS-166, MSG-189, AVT-382. [Online]. Available at: https://www.sto.nato.int/publications/Pages/default.aspx (Accessed: 15 January 2024); MCDC – FUT-LEAD. [Online]. Available at: https://www.act.nato.int/wp-content/uploads/2023/05/2020_mcdc-futlead.pdf (Accessed: 15 January 2024); HPE/HPO. [Online]. Available at: https://gids-hamburg.de/wp-content/uploads/2021/04/2021-03-22_MCDC_HPEO_Project_Report_final-1.pdf (Accessed: 15 January 2024); MUAAR. [Online]. Available at: https://www.act.nato.int/wp-content/uploads/2023/05/2020_mcdc-muaar.pdf (Accessed: 15 January 2024); InfoAgeC2. [Online]. Available at: https://cdissz.wp.mil.pl/u/MCDC_Overview.pdf (Accessed: 15 January 2024).

60 NATO STO SAS-164, 21st Century Force Development, (2020-2022). [Online]. Available at: https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/STO-MP-SAS-OCS-ORA-2023/MP-SAS-OCS-ORA-2023-05.pdf (Accessed: 15 January 2024).

framework seems inevitable for the armed forces to perform effectively on the future battlefield.

4.2.6. International cooperation

International cooperation and standardisation in the military C2 domain are essential for creating a cohesive and efficient framework for joint multinational operations. In coalitions of weaker nations, there is typically no other way to counter a powerful adversary effectively. The standardisation process includes harmonising communication protocols, data formats, operational procedures, and technological systems as well as joint training and exercises to evaluate the fundamental principles of that effort. Organisations such as NATO have professionalised such efforts, developing standardised practices and technologies that member countries adhere to and facilitating interoperability and cooperation. Nevertheless, achieving even essential standardisation is a complex and long-term process involving negotiations and compromises among participating nations, each with unique military practices and strategic priorities. Despite these challenges, the pursuit of standardisation in international military cooperation remains a critical goal, as it significantly strengthens the collective ability of allied nations to respond to global security challenges in a coordinated and effective manner.

4.2.7. Brief summary

The integration of AI into C2 structures and systems is primarily motivated by the need to rapidly process and understand the vast amounts of data generated from various components, systems, sources, and sensors (satellites, sensors, ISR, military entities, cybersecurity systems, etc.). As warfare becomes more network-centric and data-driven, traditional human-centric C2 systems will struggle to keep pace with the speed and precision required for operational decision-making, and this is happening in the contemporary world. AI can offer quick predictive analytics, automated planning, and real-time threat assessment, thus enhancing situational awareness and operational planning, which play a decisive role on the battlefield. The shift towards AI-enhanced C2 is expected to unfold progressively as AI technology matures and proves its reliability and effectiveness in military applications. This transition will likely be gradual, beginning with AI as a decision-support tool and evolving into more autonomous functions such as trust in technology development. The timeframe for this evolution depends on technological advancements, operational testing, the validation of AI systems, and the establishment of ethical and legal frameworks for their use in military settings. By the late 2020s or the early 2030s, we might see a more noticeable integration of AI into C2 systems, marking a significant shift in how military operations are conducted.

4.3. Swarming, Autonomy, and Real-Time issues as fundamental future military attributes

As predicted in the 1980s and demonstrated in the latest conflicts, autonomous systems are revolutionising warfare in the 21st century, marking a paradigm shift in the military domain. These systems, which range from drones and unmanned vehicles to AI-driven sensor networks, have dramatically changed the nature and dynamics of modern combat operations. The critical aspect of autonomy in modern warfare is its potential to conduct operations faster, for longer durations, and with a level of precision that is challenging for human-operated systems.

Beyond individual tasks, autonomous systems contribute to a broader network-centric warfare approach, operating in extreme numbers as a fully integrated multi-robot system, and communicating and coordinating actions simultaneously to achieve operational goals quickly and effectively. Based on the principles of algorithmic behaviour, the large swarms of autonomous systems present a critical threat, and the effectiveness of coordinated swarms could be exponentially increased (compared with uncoordinated swarms). Such swarms could outperform any contemporary defence system by quickly flooding the engagement area with an enormous number of robotic entities ready to be sacrificed in favour of mission objective fulfilment.

Another factor that favours autonomous systems is their low latencies and unprecedented reaction speeds. The future effectiveness of warfare depends heavily on the ability to respond within the shortest possible time. Human reaction times typically vary between 200 and 250 milliseconds, and reaction times tend to slow down with ageing.[61] In contrast, electronic systems can theoretically respond in less than a millisecond, in practical scenarios, between 30 and 50 milliseconds. This shift towards autonomous warfare enhances military capabilities and reshapes engagement, decision-making, and force-deployment principles. Systems with autonomous features continue to undertake roles exclusive to humans in previous decades, and this trend seems to be evolving exponentially. However, as these systems become more prevalent, they also raise important ethical, legal, and strategic questions, particularly regarding decision-making in combat situations and the future role of human soldiers. Autonomous systems have significant military potential in various fields, which could also be utilised in civilian domains and could bring substantial benefits, such as:

- Enhanced situational awareness – due to the advanced sensing and information processing,
- Reduced risk to humans – due to the distant or automatic control,
- Increased operational efficiency – due to advanced automation, unprecedented performance in time-critical operations, and enormous numbers of coordinated systems applied

61 Woods et al., 2015, p. 10.

- Precision and accuracy – enabled by advanced mechatronics and electronics advancements.

Various autonomous systems play essential roles in the modern military landscape, each contributing unique capabilities to defence strategies. Typically, these systems are arranged according to their operational domains, covering the most common applications.

- Unmanned aerial vehicles (UAVs) and drones are becoming increasingly prominent and are being utilised for reconnaissance, surveillance, and precision strikes.
- Ground-based autonomous vehicles such as unmanned ground vehicles (UGVs) and unattended ground sensors (UGS[62]) enhance logistics, surveillance, and battlefield support capabilities.
- Autonomous naval systems are transforming maritime operations into unmanned surface vehicles and underwater vehicles (UUVs). They play critical roles in mine detection, anti-submarine warfare, and oceanographic research by providing greater operational reach and requiring less human interaction.

There is expected to be an extension to the space domain and potentially new domains in future warfare (for instance, underground, human mind[63]). All the mentioned systems overlap significantly with civilian domains (such as transportation, surveillance, supervision, and security), and any technological breakthrough in these areas will inevitably lead to an increase in trust within the civilian domain and encouragement for a broader spectrum of its applications. Because military requirements are usually much higher than those in civilian domains (even in industrial or security areas), limitations in the legal framework and cost-benefit analyses are the primary obstacles to civilian adoption of military technology, in addition to technology maturity issues.

4.3.1. Key Challenges and Limitations of Autonomous Systems

Although they offer significant advantages and capabilities, autonomous systems face many critical challenges that affect their development, deployment, and effective operation, such as technical complexity, AI and ML limitations, coordination, communication, safety, reliability, human–machine interface, integration of cyber vulnerabilities, and regulatory and standards development. Although the detailed list and description of these challenges significantly exceed the framework of this chapter, two significant challenges of contemporary autonomous systems limit their comprehensive employment in operational applications. Although numerous promising solutions and theoretical approaches exist, it will likely take several years of

62 UGS could also refer to the term unmanned ground system, which some armies use instead of UGV.
63 Gregg, 2016.

additional development to reach an operational readiness state. These challenges are navigation in complex environments (in all domains) and automated operational reasoning and coordination.

4.3.2. Autonomous navigation

One of the most challenging tasks for unmanned systems, especially in the ground domain, is "off-road" autonomous navigation,[64] which proves the DARPA RACER[65] challenge released in 2021. Despite being theoretically solved[66] no solution has yet been effectively implemented, which introduces a key milestone for the explosion of UGV applications across all areas in the future. The critical part of "off-road" navigation is the correct "cost-map" calculation within the path planning process, which is theoretically solved. Nevertheless, it places a high demand on several sensors (such as the Light Detection and Ranging (LIDAR), camera, RADAR, and Hyperspectral sensing), data processing, and traversability calculations to implement Multi-Body Simulations (MBS) physical vehicle simulations and integrate other machine learning principles and methods. This theoretically proven approach is hard to apply in real-time with contemporary in-vehicle computing technology, and currently, it is one of the most important research topics within the autonomy domain.

UAV navigation is a very complex problem as well, but due to the 3D path planning options (in contrast to the ground, which is only 2D) and usually an "obstacle-friendly environment", it is far easier to compute and optimize in real-time. It has been proven over two decades of extensive experience in military applications and civilian expansion. One of the most challenging issues within the UAV domain today is the coordination of many entities in an obstacle-dense environment, which concentrates a significant research effort on this field. Nevertheless, advanced concepts and demonstrators[67] that perform an effective UAV swarm motion through dense woods and jungles already exist. Thus, potential military applications are in sight, with the potential to dramatically change combat tactics and efficiency.

4.3.3. Operational reasoning

Tactical autonomy is one of the complex and critical capabilities of future autonomous systems that will enable them to effectively replace soldiers on the battlefield.[68] AOR is based on COP quantification (math transformation), modelling, and automated friendly force COA delivery in the context of the latest battlefield configuration and extreme levels of detail for global plan consolidation for each automated

64 Loganathan and Ahmad, 2023.
65 Ackerman, 2022.
66 Thakker, 2021.
67 Gent, 2020.
68 Hagos and Rawat, 2022.

tactical entity. Several approaches exist to find a solution to this problem, and one of the initial concepts was introduced in the DARPA Deep Green project; however, complexity, computation and communication issues, lack of deep understanding, and operationally successful experiments prevent this field from evolving dynamically, even though it is extremally important for dominance on the future battlefield. More comprehensive information on individual approaches and solutions can be found online.[69]

These technological challenges have significant dual-use effects in various civilian fields and, like in the military, will be critical milestones in the automation of a series of tasks that severely impact particular human domains, such as transportation, forestry, the mining industry, critical infrastructure supervision and service, and project management.

5. Military technology impacts human domains and dual-use aspects

Integrating advanced technology into the military significantly affects various human domains within this unique environment, such as the social, psychological, cognitive, and cultural aspects. Sophisticated communication tools and networks have altered the dynamics of interactions among military personnel, enhancing coordination and potentially creating dependencies on digital forms of communication. The demands of operating advanced technologies can increase competency requirements and stress, particularly in high-stakes or combat situations. Advanced technologies require the development of new skills, continuous learning, and adaptation. While advanced technologies bring numerous operational advantages to the military, their influence on individuals requires careful organisation to reach their full potential while protecting military personnel's mental resilience, health, and readiness. The following specific domains show how sophisticated military technology has affected the human domain (which could benefit from the technology itself or experience from military operational domains):

5.1. Social Impact

Sophisticated communication networks and collaboration platforms have revolutionised how military personnel communicate and coordinate, overcoming geographical barriers and enabling the real-time and efficient exchange of information. However, this reliance on digital communication can also affect traditional face-to-face interactions, potentially affecting unit cohesion and developing interpersonal

69 Mazal, 2022; Mazal, 2020.

relationships that are crucial for teamwork in high-pressure environments. Technology has reshaped military social relations by introducing diverse and remotely operated platforms, leading to shifts in traditional roles and responsibilities. This evolution requires adaptations in the command structure and operational culture, posing challenges and opportunities for social integration and establishing effective team dynamics. Additionally, because of advanced technology, digital connectivity brings the external world closer to military personnel, even in deployed locations, thereby impacting the traditional boundaries between service members' professional and personal lives. While advanced technology offers significant operational benefits, its influence on the social aspects of military life requires careful consideration to maintain robust, cohesive, and adaptable military communities. This aspect is also valid in the civilian domain, and research on sociotechnological impacts could benefit from military experience in advance.

5.2. Psychological impact

The psychological impact of advanced military technologies is fundamental and complex, influencing the mental health and operational mindset of military personnel.[70] On the one hand, these technologies can improve soldiers' capabilities, situational awareness, and safety, which can boost their morale and confidence. Tools such as exoskeletons, enhanced surveillance systems, and AI-assisted decision-making platforms can reduce the physical stress and fatigue of warfare and improve the psychological status of personnel. On the other hand, the high risk factors of operating sophisticated technology in life-or-death situations can elevate stress levels, leading to increased pressure and anxiety. The remote nature of advanced warfare technologies such as drones can also create psychological distance from the battlefield, leading to unique challenges in processing combat experiences and outcomes. Moreover, the rapid pace of technological change requires continuous adaptation and learning, which can be mentally demanding. Concerns about overreliance on technology and the potential loss of fundamental military skills may also contribute to psychological tensions. Thus, while advanced technologies in the military have significant tactical advantages, their psychological impacts are complex and require a comprehensive approach to ensure military personnel's mental resilience and readiness, taking into account that reliance on advanced technologies with a lack of understanding of its functionalities and impacts is inevitable and introduces a significant challenge for the future of man-machine relations (this aspect has many counterparts in civilian jobs, from the air traffic controller to the police officer).

70 Lovalekar et al., 2018.

5.3. Cognitive impact

The effect of advanced military technologies on cognition is a critical aspect of modern warfare that significantly influences how military personnel perceive and process information,[71] make decisions, and adapt to complex environments. These technologies often enable enhanced data processing and provide situational awareness tools, aiding quicker and more informed decision-making under pressure. Advanced AI technology can augment cognitive abilities by filtering and prioritising vast amounts of information, allowing soldiers to focus on high-level strategic thinking rather than being overwhelmed by data. However, this reliance on technological assistance also raises concerns about cognitive atrophy – potentially diminishing essential skills such as navigation, observation, and instinctual decision-making–traditionally improved through experience and practice. Moreover, constant interaction with advanced systems requires a high level of cognitive flexibility and continuous learning, as soldiers must keep pace with rapidly evolving technologies and shifting operational paradigms. This need for constant upskilling can be mentally stimulating and demanding, highlighting the need for balanced cognitive engagement and training with careful consideration of the cognitive load and training methodologies. In the future, the trend of advanced automation, sensing, and AI processing within almost all domains will inevitably lead to a dramatic reduction of mental load in humans, enabling individuals to focus on strategic goal selection and supervision over mid to long-term periods. The acceleration of this trend in the military domain will immediately affect the commercial (mainly but not only industrial) sector and vice versa.

5.4. Economic impact

The economic impact of advanced military technologies is complex and influences national budgets, the defence industry, and broader economic landscapes. Investments in advanced military technologies can impose a significant financial burden on governments. However, the beneficial outputs associated with research, development, and acquisition can potentially lead to improvements in different sectors, as human history has proven. The defence industry significantly contributes to technological innovation, creating employment opportunities and promoting economic growth. This often sets the pace for commercial technological development and leads to strategic opportunities, in that countries at the forefront of military technology may acquire geopolitical advantages that could affect the dynamics of economic power and global commerce. Thus, although advanced military technologies demand considerable financial and human resources, they also act as catalysts for technological progress and economic development, underscoring the need for strategic and balanced investments.

71 Billing, 2021.

5.5. Cultural impact

The cultural impact of advanced military technologies extends beyond the boundaries of defence and influences broader societal perspectives, values, and narratives. These technologies often become symbols of national pride and power, shaping a nation's cultural identity and global perceptions. For instance, aerospace, nuclear, AI, missile, and other military technological advancements reflect a country's scientific and technological achievements, inspiring national cohesion and ambition. However, there has also been a cultural shift in the perception of warfare and the military's role, driven by technologies that change the nature of combat. This shift can lead to debates and re-evaluations of challenging traditional martial values and hero archetypes. Moreover, the integration of advanced technologies into military training and operations affects the culture within the military itself, altering traditions, practices, and soldiers' experiences. Thus, while these technologies are primarily tools of defence and security, their cultural consequences are significant and shape narratives, values, and perceptions within and beyond the military sphere.

5.6. Environmental impact

The environmental impacts of advanced military technologies are a growing concern, with both direct and indirect effects on global ecosystem. Developing, testing, and deploying these technologies can have significant ecological consequences, considering that advanced military technologies are associated with accelerating the arms race, increasing weaponry production, and worsening environmental impacts in multiple sectors. While the primary focus of military technology is national security, there is increasing awareness and responsibility towards minimising its ecological footprint. This involves implementing more sustainable practices in production, operation, and disposal and considering the environmental impacts of designing and developing new technologies. Balancing these considerations is crucial to ensure that efforts to enhance defence capabilities do not come at the cost of environmental health and sustainability, as in other domains (forestry, energy production, intensive agriculture, space, transport, and many others).

5.7. Political impact

The political impact of advanced military technologies is essential and far-reaching, as it influences the dynamics of international relations and domestic policy decisions. Countries with cutting-edge military technologies often possess significant geopolitical influence on the global stage, using their technological superiority for diplomacy or deterrence. Developing and deploying these technologies can shift the balance of power, leading to strategic alliances, softening tensions, and increasing the pace of the arms race. Domestically, the decision to invest in advanced military technologies can be a sensitive political issue that is often debated in terms of national security priorities versus other societal needs. These technologies also shape defence policies and military doctrines, influencing how nations perceive and respond to threats. Furthermore, the use and export of military technology can become a significant consideration in foreign policy, affecting international trade agreements and diplomatic relations. The governance and regulation of these technologies impose substantial political challenges, requiring cross-border cooperation and the establishment of international rules and agreements. Thus, advancing military technologies is not just a matter of defence; it is also linked to national policy, affecting the domestic and international geopolitical landscape.

5.8. Ethical aspects and strategic implications

The ethical and moral implications of advanced military technologies are increasingly coming to the forefront of the defence discourse, posing philosophical questions and challenges.[72] Technologies such as autonomous weapons systems, AI-driven decision-making tools, and enhanced surveillance capabilities have raised significant ethical dilemmas with potentially critical strategic consequences. For example, delegating essential combat decisions to automated systems raises issues of accountability, responsibility, and the moral implication of reduced human oversight in life-and-death situations. The potential for AI to make decisions based on algorithms that may not fully understand complex human ethical considerations adds another layer of concern. Within this area, a series of terms and standards describe the level of autonomy, automation,[73] or level of human involvement within automated processes, such as (i) Human-in-the-loop – a concept where a human operator is directly involved in the decision-making or control process of a robotic system, (ii) Human-on-the-loop–a concept where a human supervisor monitors and oversees an autonomous system but does not directly control each of its actions, and (iii) Human-out-of-the-loop – a concept where humans are not actively involved in controlling, monitoring, or intervening in the operations of the robotic systems.

The use of advanced surveillance technologies and cyber warfare tools also raises privacy issues, and there is potential for abuse of power, affecting both combatant and civilian populations. These technologies also force a re-evaluation of the established norms and laws of warfare, challenging traditional conceptions of

72 Committee on Ethical and Societal Implications of Advances in Militarily Significant Technologies that are Rapidly Changing and Increasingly Globally Accessible, 2014.

73 Autonomy levels, particularly in the context of autonomous vehicles, are typically defined on a scale that measures the degree to which a system is capable of operating without human intervention. Multiple versions of these scales exist, but they all essentially describe the spectrum between the manned and fully automated (autonomous) systems. The Society of Automotive Engineers (SAE) defines these levels for vehicles as follows: Level 0 – No automation, Level 1 – Driver assistance, Level 2 – Partial automation, Level 3 – Conditional automation, Level 4 – High automation, Level 5 – Full automation.

honour, courage, rules of engagement, and combat ethics. Integrating advanced technologies into military operations requires a broader ethical agreement and algorithmic (logical) framework (what-if), clear guidelines, and ongoing dialogue among military leaders, policymakers, ethicists, and the wider society to navigate these complex moral affairs responsibly. In the international environment, various campaigns and initiatives have aimed to establish ethical frameworks for employing advanced military technology. These campaigns often involve international organisations, governments, nongovernmental organisations (NGOs), academic institutions, and sometimes the military and defence industries. The key focus areas are as follows:

- Autonomous weapons systems: Initiatives such as the Campaign to Stop Killer Robots focus on a pre-emptive ban on developing and using lethal autonomous weapons systems (LAWS).
- Cyber Warfare: With the increasing prevalence of cyber warfare, attempts are being made to create global standards and ethical principles for cyber operations (especially those targeting civilian infrastructure and noncombatants).
- Artificial Intelligence in Warfare: Organisations such as the Institute for Ethics and Emerging Technologies and the Future of Life Institute focus on the ethical use of AI in military contexts, promoting regulations that prevent misuse and ensuring that AI is developed and used in alignment with human values.
- Nuclear Non-Proliferation and Disarmament: Groups such as the International Campaign to Abolish Nuclear Weapons (ICAN) work towards the global elimination of atomic weapons, emphasising the catastrophic humanitarian consequences of their use.
- Biotechnology and Chemical Weapons: Campaigns like the International Committee of the Red Cross focus on the ethical implications of biotechnological advances in warfare, encouraging commitment and strengthening of international laws like the Chemical Weapons Convention and Biological Weapons Convention.
- Surveillance and Privacy: With advanced technologies enabling unprecedented levels of surveillance, campaigns have focused on balancing national security interests with individual privacy rights, such as those led by the Electronic Frontier Foundation.
- Military AI Research Oversight: Academic and research groups have called for responsible AI research in military applications, emphasising the need for ethical oversight and transparency in military-funded AI research projects.
- International Laws and Treaties: Efforts are being made to update and expand the existing international humanitarian laws and treaties to incorporate new technologies and ensure that they are used in compliance with international law and ethical standards.

Ethical campaigns and initiatives play a crucial role in shaping the discourse around developing and deploying advanced military technologies, aiming to influence policymakers and the public towards an international consensus for responsible and ethical technological advancement in defence. While these activities are crucial for guiding accountable development and use, they present serious risks and challenges, such as:

- Innovation slowdown: Strict ethical rules or calls for technology bans may obstruct innovation and research, putting a nation or alliance at a strategic disadvantage, particularly if potential adversaries continue to develop such technology. Furthermore, they may have negative economic impacts on the defence industry, which is a significant part of many countries' economies.
- Difficulties in reaching consensus: The existence of diverse ethical, cultural, and political viewpoints worldwide leads to challenges in reaching a consensus on regulations. International policies may contain conflicts or inconsistencies owing to ethical divergence between nations.
- Rapid pace of technological advancement: The rapid pace of technological advancement can surpass the development of ethical frameworks and regulations, resulting in a gap where new technologies are used without comprehensive ethical guidelines.
- Dual-use dilemmas: Strict regulations based on ethical campaigns may unintentionally delay beneficial civilian technological advancements and applications of many advanced military technologies with dual-use applications.
- Enforcement challenges: Enforcing ethical guidelines globally is challenging due to varying capabilities and priorities in different countries. Noncompliance or private development of banned technologies can pose significant issues.
- Security dilemmas: The development of military technologies often leads to security dilemmas in which nations feel threatened and respond with their developments, escalating an arms race.
- Public perception and trust: These campaigns may cause people to fear or mistrust advanced technologies, leading to resistance to their beneficial use.

While ethical debates are essential for building consensus on the responsible use of advanced military technologies, there is a significant risk of overestimating particular issues, based on artificial or unrealistic scenarios. These scenarios, while well-intentioned, could be subtly influenced by potential opponents to achieve specific goals. Thus, any activity within this scope should maintain a deep and rational understanding of all the discussed areas and possible aspects guided by competent personnel.

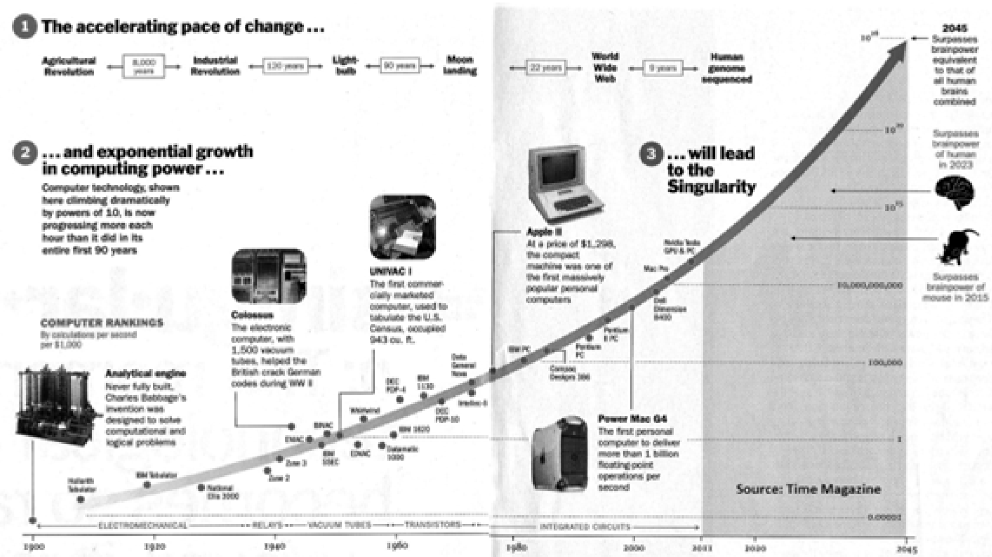
5.9. Short and mid-term future uncertainty

An accurate prognosis is crucial for achieving future goals and operational efficiency within the security environment. Unfortunately, it is fundamentally impossible to predict the future of complex socioeconomic systems accurately. Concerning the chance of a correct prognosis based on contemporary facts and development trends, there is only a slight chance of estimating short or mid-term future evolution in the military. However, we can track some historically proven and correct estimations in the military, such as:

– Guerrilla warfare: Mao Zedong and Che Guevara predicted that guerrilla warfare would be effective against conventional military forces. This warfare became effective in the 20th/21st centuries, and their prediction has been proven in many conflicts, such as the Vietnam War, the Cuban Revolution, and various African and Asian independence movements.
– Blitzkrieg: Heinz Guderian, inspired by the ideas of British military strategist J.F.C. Fuller and others, forecasted the effectiveness of fast and intensively coordinated combat using tanks, aircraft, and motorised infantry. This proved highly effective in the early years of World War II.
– Nuclear warfare: Albert Einstein and Winston Churchill forecasted the devastating potential of atomic weapons, which led to a doctrine of mutually assured destruction during the Cold War. This doctrine was maintained throughout the Cold War to prevent large-scale conflicts.
– Air superiority: Theorists such as Italian General Giulio Douhet argued in the 1920s that air power would decide future wars. This has been proven in many conflicts, and air superiority is critical in almost all wars.
– Cyber warfare: In the late 20th and early 21st centuries, experts began predicting the rise of cyber warfare, such as hacking, and digital disruption in military strategies. One example is the Stuxnet virus attacks on Iranian nuclear facilities, and there are many other instances of cyberespionage and sabotage.
– The rise of drones: Military analysts have predicted that drones will be extensively utilised in warfare. This prediction has become true in modern conflicts in which drones have replaced human soldiers in their battle roles and have significantly altered the nature of warfare.

However, the rapid pace of technological advancement and its impact on global society make predictions even more difficult in today's operating environment. This creates considerable uncertainty and has drawn the attention of many technological experts and futurologists. Kurzweil's path to singularity shows how computing power (a single supercomputer) is growing exponentially, surpassing the performance of the human brain in 2021 and potentially of all humanity by 2045 (see Figure 3).

Figure 4: Ray Kurzweil's prediction on the path to singularity (source: Time Magazine)



However important, computing performance is required to surpass the human intellect, and the critical aspects of intelligent machines lie in the complexity of AI algorithms, which can compete with humans at all levels of intelligence. We distinguish between two levels of AI intelligence: weak and strong.

Weak intelligence, also known as narrow AI, refers to a type of AI that is designed and trained for a specific task. Unlike strong AI, which aims to replicate human-like awareness and cognitive abilities, weak AI operates within a limited predefined range or context and is programmed to perform specific functions. It does not possess the understanding, consciousness, or ability to apply knowledge or skills to contexts beyond its specific software design. Examples of weak AI are present in everyday life and include virtual assistants, recommendation systems, facial recognition, and email filtering. The development of weak AI has significantly contributed to efficiency in various sectors by automating routine tasks, enhancing user experience, and improving decision-making processes through data analysis. Weak AI already competes with or significantly outperforms the human brain in various tasks[74] such as imagery recognition, planning, and desk game performance, and this trend continues within the broader AI field.

74 *A graph showing how artificial intelligence (AI) has overtaken humans and overtaking them is like this,* 2017.

Figure 5: AI visualisation of the path to singularity (source: DALLE-E)

Strong AI (Artificial general intelligence) refers to a type of AI that can understand, learn, and apply its intelligence to solve any problem with the same level of development as a human brain. The characteristics of Strong AI are as follows:

- Generalised learning ability
- Understanding and reasoning
- Consciousness and self-awareness

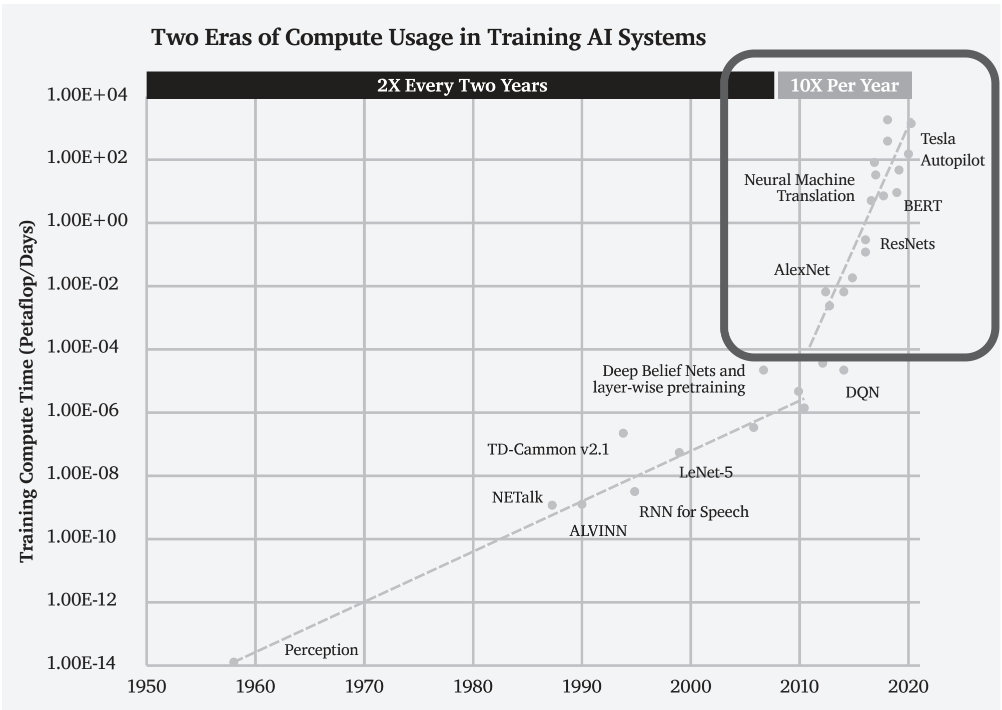
Strong AI remains a theoretical concept, and there is no clear evidence that an initial successful solution is yet in sight. In any case, it provides an extremely attractive and mind-breaking social theme with significant ethical, philosophical, and technical challenges, including the nature of consciousness, the rights of artificial entities, and their impact on society.

Nevertheless, based on the development trend of AI performance, mainly coming from the deep neuronal network field, there is a dramatic increase in performance that overcomes Moore's law (Moore's law is the theory that the number of transistors on an integrated circuit will double approximately every 1.5 years. According to James Wang,[75] a former NVIDIA (a US AI leading company) engineer who was part of launching the GeForce Experience, the advancement of AI is 5 to 100 times faster

75 *Artificial intelligence is growing dozens of times faster than Moore's Law*, 2020.

than Moore's Law, as illustrated in Figure 6. As the necessary conditions for General AI gradually reach readiness, its emergence in the near future seems increasingly realistic. However, the impact of General AI on the future remains highly uncertain and could easily be seen as a subject more fitting for science fiction.

Figure 6: Graph of AI performance growth compared to Moore's law (source: ARK Investment Management LLC, "AI and Compute", OpenAI)



5.10. Recommendations for policymakers, military strategists, and tech developers

The effective development of military technology has seriously affected national security and strategies. In light of potential opponents' technological advancements, the government should be vigilant in preventing any potential loss of operational performance that cannot be compensated for through other strategies like diplomacy, human force superiority, or environments that prohibit the use of certain technologies. The effective development of any technological sector relies on several simple (though practically challenging) principles that must be considered and carefully maintained, such as:

- Continuous evolvement – Any development area suffers from breaks and restarts, leading to the loss of skilled and experienced personnel.. Adequate

technological progress necessitates continuous evolution and incremental capacity increases based on needs and conditions.
- Budget: An appropriate budget is foundational for the effective development of military technologies, enabling sustained innovation, attracting and retaining talent, maintaining advanced research facilities, and responding to emerging threats. It is crucial to accomplish the entire technology development lifecycle from initial R&D to full-scale deployment.
- Infrastructure This includes local facilities and a broader interconnection within the scientific and industrial community to create an efficient architecture of departments and institutions that provide and maintain excellence in particular technological areas.
- Human capital encompasses the knowledge, skills, and abilities that individuals possess and which are essential for every stage of the technological development cycle, from research and development to production and deployment.
- International cooperation plays a fundamental role in advanced development and offers several key advantages. Challenges usually do not outweigh the positives of state-of-the-art awareness, resource sharing, specialisation and expertise, standardisation and interoperability, innovation, cross-pollination of ideas, access to markets and technologies, and enhanced cooperation in other areas.

6. Conclusion

The experience gained from the history of warfare is that the level of technological progress is a crucial aspect that cannot be compensated for in any other way (like numerical superiority). This fact directly touches on issues such as the fundamental nature of warfare and operational effectiveness; these issues inevitably lead to the development of autonomous machines with capabilities (and cost) against which humans will no longer be able to perform effectively because of their very rapid response capabilities. Currently, we are still at the beginning of our understanding of this phenomenon. However, current technological demonstrators and simulations clearly show the development lines of the future battlefield, where it will no longer make sense to deploy human soldiers because the fight between human soldiers and autonomous robots will inevitably lead to the loss of human lives). Therefore, the robotisation of combat will be crucial for dominance on the modern battlefield, and the technological superiority of autonomous systems will play a decisive role.

From a global perspective, the world is in a relatively advanced stage of robotisation and implementation of AI, and many initial demonstrators have shown the immense short- and medium-term potential of robotics. Many new components are already available, and must be integrated or modified for specific purposes.

One of the most critical components of autonomous systems is coordinated swarm behaviour (focusing on a common operational goal), particularly in the context of enormous numbers of these entities on the battlefield, which will become a dramatically different environment from the relatively slowly evolving battlefields today. Without a doubt, technology will shape the nature of close-quarters combat in the future. The current conflict in Ukraine, where tens of thousands of drones are employed daily, is a clear example of the logically pragmatic repercussions of this reality.

Based on the prognosis from various sources, state-of-the-art technology, and the evolution of contemporary combat (Ukraine, Gaza. etc.), several critical technologies and areas are expected to shape the future of military development and warfare, closely linked with potential dual-use effects in this decade.

Advanced simulation technology will be a key component of future military dominance on the battlefield. The use of mathematical modelling and simulation[76] is a key trend[77] in scientific, industrial, and other domains for more than three decades. The quality of the solutions obtained through modelling and simulation depends on the nature of the problem being solved and the environment in which the simulation occurs. Simulation fidelity is on the rise to deliver unprecedented detail within augmented environment complexity, enabling advanced analysis and decision-making, implementation of AI and machine learning models, virtual reality (VR) and augmented reality (AR) systems, combat simulation software and streaming platforms, interactive digital maps and geographic information systems (GIS), Cyber Warfare, Logistics Support, and Unmanned Systems Simulation. The development of advanced military simulation technologies could inspire and motivate civilian applications with a particular military overlap from government strategy to industry and security, with the pursuit of maximum performance and cost-effectiveness.

AI and machine learning will play an increasingly important role in various fields, such as data analysis, predictive analytics, autonomous systems, and decision-making processes. Nowadays, LLMs[78] have been sufficiently developed to reduce the workload of staff members responsible for routine administration. As is known from the past, they will bridge the gap between now and fully automated combat

76 This discipline aims to "virtualize" problems by converting them into a virtual domain on computers that approximates the real world, through mathematical models and computer simulations.

77 The primary reason for this approach is that a many problems have become so complex that it is impossible to find a direct solution through analysis. As a result, the so-called evolutionary method is often used, where input parameters are experimentally adjusted to meet the desired output of the simulation.

78 LLM stands for "large language model". This refers to a type of artificial intelligence model that is specifically designed to understand, generate, and interact with human language on a large scale. These models are a subset of machine learning and are based on neural networks, particularly a class known as transformers.

in the future by following different management principles. AI and ML technology can potentially improve military decision-making at all levels of command, but broader operationalisation of this concept will require additional experimentation and testing to build necessary trust. Operational AI, despite some uncertainties and limitations, could relatively soon meet the primary requirement of avoiding tactical mistakes by identifying a system's critical state, which requires a particular interest and resolution (In the realm of military operations, this includes detecting adversary movements in time to prevent surprise attacks on friendly forces). The evolution of AI in the military will contribute to civilian progress and vice versa. Similar to hybrid warfare, AI will likely become omnipresent, blurring the boundaries between application domains.

The ongoing need for agility and development of rapid counter-measures will drive innovative and flexible solutions to the adaptive serial production lines, logistics and supply chains, software development, predictive diagnostics, and real-time identification of weak points in the field (utilising technologies such as 3D Printing and Additive Manufacturing). This will also affect many aspects of the civilian domain, such as the development of in-home, portable and adaptive production systems, including advanced self-diagnostics and digital-twin area evolution. There is a general consensus that cybersecurity and cyber warfare will become crucial for future defence and civilian applications. The future hybrid conflict will target the civilian infrastructure with a similar intensity as military forces and assets. Thus, cyber warfare capabilities will be a crucial component of military operations, mainly targeted to the critical sectors of the military systems, like communication infrastructure, networks, databases, and cloud services.

Autonomous military robots (UAVs, UGVs, and UUVs) have undergone a dynamic and inevitable technological evolution, showing their clear potential to outperform humans in all combat functions and domains. This will lead to an explosion of potentially new or improved contemporary civilian applications in industry, agriculture, security, medicine, transportation, sports, and leisure.

Quantum computing and communications have the potential to revolutionise the military and civilian sectors through advancements in secure communication, computing power, and encryption. Although it is at an early stage, significant progress is expected in this area within the next few years. This could introduce dramatic technological breakthroughs and unimaginable opportunities, such as solutions for very complex tasks and safe and real-time intergalactic communication.

Space capabilities and the development of anti-satellite and space defence weapons, satellites, and space technology for communication, surveillance, and navigation are expanding rapidly and will continue to be essential for military operations over the next decade.

Hypersonic weapons provide new precision attack and defence capabilities, posing unique challenges for existing defence systems. DEWs could outperform this technology in countermeasures and significantly degrade its potential. DEWs provide precision attack and defence capabilities against other threats like drones and aircraft, presenting a vast potential for future warfare, so that enormous effort is dedicated to this area.

Advanced materials and nanotechnology allow the creation of more robust and lighter military equipment, from personal armour to vehicles, and present one of the most intense development fields in the civilian domain. This field possesses enormous potential, and development in this area is a logical outcome of military and civilian needs in almost all domains. Also, in the modern world, the military, industry, space, electronics, and other domains will rely substantially on advanced batteries and new power generation methods for their energy needs. This area is growing dynamically and sets a critical operational limit within different domains.

Because recent experiences demonstrate that the cyber domain is being heavily exploited by civilian population, it is reasonable to assume that future wars will become more hybrid and interwoven with the civilian sector. This leads to closer cohesion regarding dual-use technologies and production benefits, which could be interconnected so deeply that the functionality within a particular domain will be driven or defined only by SW features, like those in many technological components today (e.g. car engines). Although it is expected that these domains will advance simultaneously, the world will likely never return to the Cold War era when "doctrine pulled technology". Therefore, dual-use technologies are likely to be more closely fused, and the potential benefits of successful developments in one domain will immediately appear in others.

A critical step in the dynamic evolution of advanced technologies within armies is establishing trust in advanced automation (autonomy), including in AI/ML and other EDT-based technologies. This is a crucial and complex challenge for all armies worldwide. It requires a multifaceted approach, addressing technical reliability, ethical governance,[79] user training, involvement in the development process, and positive experiences/examples (i.e. demonstrating successful instances where advanced technologies have enhanced mission effectiveness, reduced casualties, or aided in humanitarian efforts). In conclusion, it is important to note that extreme conservatism regarding the implementation of cutting-edge technology will significantly reduce the military's ability to respond to rapidly developing operating environment issues. This could have lethal repercussions.

79 Chameau, 2014.

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