Safety & Defense 8(1) (2022)
DoI: https://doi.org/10.37105/sd.170

Development of Security Technologies by NATO: Current Status and Development Prospects

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Received: 03 October 2021 | Revised: 18 May 2022
Accepted: 18 May 2022 | Available online: 30 June 2022

Abstract

The aim of this paper is to determine the current development status of individual NATO development areas as well as to indicate further research directions. Six research areas in which NATO develops its technologies that influence the high militarization level of the alliance were shown. These include Big Data, Artificial Intelligence, autonomy, quantum technology, space technology and hypersonic capabilities of the alliance, as well as Biotechnology and Human Enhancement. The development of Big Data will significantly increase the alliance's threat detection, reconnaissance, and identification capabilities and allow for the diagnosis of anomalies and internal threats. Artificial Intelligence can be used for effective military operations (aircraft air combat) and also in intelligence analysis for data collection, processing and search. Autonomy in allied operations will allow the use of unmanned aerial systems and their operations in urbanized terrain and increase situational awareness through continuous monitoring of the combat environment. Quantum technology will allow for increased allied capabilities in the areas of communications, information technology, precision navigation and time delivery systems, and sensing. Space technologies and the acquisition of hypersonic technologies will contribute to reconnaissance and intelligence capabilities, and hypersonic missiles will further provide strategic warfare assets. The research results on biotechnology and Human Enhancement by NATO will provide knowledge for enhancing the psychophysical capabilities of soldiers.

Keywords: directions of development, NATO, order safety, technologies

1. Introduction

New and innovative technologies can provide a military advantage to a country or alliance. This is why NATO, as well as its individual member states, constantly strive to develop them. It should be taken into account that the development of these technologies is a long and costly process and not always successful. However, it ensures security and highly classifies a given actor, influencing its militarization level.

Preliminary studies have shown that there are several research areas in which the NATO alliance conducts their investigations at different developmental stages. These areas may include the development of Big Data, Artificial Intelligence (AI), Autonomy, Quantum Technologies, Space Technologies and Hypersonic Capabilities, as well as Biotechnology and Human Enhancement. The research areas so defined are the subject of this paper. The aim is to determine the current development status of each NATO development area and their further directions.

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2. Big Data development by NATO

Although Alvin Toffler first used the term Big Data in 1990 (Toffler, 1990), no single, precise definition has been defined until now. However, it can be given characteristic features. Firstly, it refers to the increasing amount of data (especially in digital form), the storage and processing of which is made possible by cheaper and more efficient information technology. Secondly, it is defined by evaluative attributes. The first characterizations of this term defined it through three attributes: volume, velocity, and variety (Kaisler et al., 2013). Subsequently, they were extended by two more: variability and complexity. Thus, models for the characteristics of Big Data term were created through various configurations and the addition of more words. One of the most popular, proposed by the IT company Oracle, defines it in the category of the so-called 4Vs (volume, velocity, variety and value – the ability to generate profit) (Oracle, n.d.). The model proposed by Oguntimilehin and Ademola categorizes Big Data using five attributes: volume, velocity, variety, variability, value, and complexity (Oguntimilehin & Ademola, 2014). Currently, a total of 15 attributes are assigned to the term (Kapil et al., 2016).

Advanced analytical methods, as well as optimization, modeling & simulation (M&S), and human factor engineering (HFE) techniques, are used to exploit data derived from Big Data. This type of integrated research effort in related literature is referred to as Advanced (Data) Analytics (Bąska et al., 2019), and the process involving big data is denoted by the acronym BDAA (Big Data and Advanced Analytics) (Mishra et al., 2019). The BDAA analysis is used by the NATO alliance. It includes four main components: collection (via sensors), communication, analysis, and decision making. The effectors that acquire data for BDAA analysis are sensors, the function of which is to provide data (information). Their operation is supported by the development of 5G communication, as well as the Internet of Things (IoT). Sensors usually form a network, and their evaluative **directions** of development indicate greater accuracy, miniaturization (molecular, nano, and quantum scales), cost reduction, and use of innovative 3D and 4D productions (NATO Science & Technology Organization, 2020).

The process of providing Big Data for NATO operations in the coming years will be supported by smart textiles, among others. The active elements in these materials will be molecular and nanoscale sensors, providing real-time monitoring of health and environment. It can be assumed that the development of advanced sensors, combined with the autonomy of systems, will significantly increase NATO's ability to detect, recognize and identify threats. In addition, the fusion of sensor data will enable the diagnosis of anomalies and thus determine the degree of reliability of the acquired information. Another effector will be the new generation of over-the-horizon (OTH) low-power radar systems, providing extensive airspace surveillance. Thanks to their design, the range of detection and tracking of air targets could increase from 350 to 1500 km. The prototype readiness of these systems (at TRL 6-7) is estimated within 5-10 years, while the development of ready-to-implement technology, at the ninth technology readiness level, is expected within 10-15 years (NATO Science & Technology Organization, 2020). Quantum sensing may be another developmental direction for Big Data. This technology will allow the detection of military objects, especially submarines and stealth aircraft. The second area of using quantum technology for NATO needs includes computational techniques, in particular encryption of communication, e.g., using Shor's quantum algorithm (Shor, 1995). Another development direction implemented by NATO will be the so-called digital twins. These represent highly detailed virtual models of processes or systems (Semeraro et al., 2021). The aim of developing a model that corresponds to the real object is to continuously improve the product through various types of computer simulations. The digital twin is generally used for monitoring, diagnostics, and prognostics – to optimize system performance, diagnose faults and errors, and perform any strength tests (Skoczylas et al., 2021). In the context of military facilities, digital twins technology refers particularly to newly built weapon systems.

3. Development of Artificial Intelligence

Another direction of new technology development undertaken by NATO is Artificial Intelligence (AI). It is understood as the ability to perform tasks that require human intelligence – learning based on experience, inferring, forecasting and taking action. Forecasts confirm that it will reach a human level of 50% before 2040, and a level of 67% may be reached before 2050 (Barrat, 2015).

Given that artificial intelligence can be considered a groundbreaking technology – it is estimated that the impact of its implementation could be comparable to the introduction of nuclear weapons (Simonite, n.d.) – it poses a very significant challenge to the NATO alliance. Currently, much conceptual work is being carried out in NATO that is expected to result in the possibility of using AI in military operations. The most promising uses of artificial intelligence include operational autonomy, intelligence analysis, battlefield robotization, and precision fire control. Analysts indicate that artificial intelligence may also be particularly important in intelligence analysis for the collection, processing, dissemination, and retrieval of search data from multiple sources – available sensors as well as archival data.

Artificial intelligence capabilities are currently being tested by the US Defense Advanced Research Projects Agency (DARPA). As a part of the first phase of implemented ACE (Air Combat Evolution) program, the capabilities of artificial intelligence were tested in close air combat, in which two F-16 multipurpose aircraft took part. Their task was to jointly defeat the enemy combat aircraft.

The test results also proved that in close air combat, an aircraft using artificial intelligence has an advantage over its human-piloted counterpart. It is estimated that the operational use of artificial intelligence in combat aviation may be possible in late 2023 or early 2024 (Katz, 2021).

4. Development of Autonomy

One area for the use of autonomy, i.e., the object's capability for self-control and decision-making, is in the air and space domain. The development of autonomy is a high priority for the alliance and partner nations. The market for autonomous systems is estimated to reach $172.3 billion by 2024 (NATO Science & Technology Organization, 2020).

Examples of such technology include swarms of autonomous air and space systems that are characterized by low production cost, high adaptability, and the ability to rapidly replenish losses. These types of mini, micro, and nanosystems, in particular, will be able to find applications in many combat environments, including urban terrain. From a design point of view, artificial mussels (AMs) with the ability to monitor the environment, particularly for heavy metal concentrations, are planned to be used in these facilities (Wu & Lau, 2013).

Another area of use for autonomous systems is in the maritime domain. They can find application in Mine Counter Measures (MCM), Anti-Access Systems (A2/AD), Anti-Submarine Warfare (ASW) tasks, and in the field of Signals Intelligence (SIGINT) and Electronic Intelligence (ELINT). It should be noted that the maritime (water) environment is particularly challenging due to the limitations of prevailing pressure, temperature, and limited navigation.

A number of changes are expected with the implementation of autonomous systems. In terms of structural alliance, it is expected that human capabilities will be gradually replaced by devices that will be used for an increasing number of tasks, carried out individually or in groups, or even in a human-machine relationship. In terms of the use of countermeasures, the use of autonomous systems such as swarms of unmanned aerial systems will require additional force protection measures with clear countermeasure capabilities. These will include both kinetic and non-kinetic combat techniques – electronic, directional weapons, cyber weapons. Another area of focus for autonomous systems is situational awareness – improved terrain reconnaissance through the use of a wide range of low-power sensors (Electro-Optical/Infra-Red, radar, magnetic sensors). They are expected to be widely used in emerging operational areas such as cyberspace, where so-called cyber agents will be increasingly used to maintain situational awareness in cyberspace (e.g., social media) as well as to identify system threats and weaknesses.

The integration of autonomous systems in the alliance is expected to be gradual, with widespread use by 2025 (NATO Science & Technology Organization, 2020). It will be necessary to solve a number of communication, control, and operational integration problems related to the use and sharing of large amount of data and the standardization of operational protocols – deconfliction, collaboration, mission planning, fusion of data in both physical and virtual environments.

5. Development of Quantum Technologies

Quantum engineering is both a field of science and technology concerned with techniques that exploit quantum phenomena – at the atomic or subatomic scale. Current military systems are based primarily on the use of classical physics. However, the so-called first quantum revolution allowed for the acquisition of knowledge that is now used in the design and manufacture of transistors, magnetic resonance imaging, or modern communication technologies.

The currently ongoing so-called second quantum revolution in the field of defense and security will develop in four key areas: communication, information technology, precision navigation systems, time provision, and sensing. In communications and information technology, quantum technologies are expected to provide faster (by several orders of magnitude) computing capabilities. Above all, it will also enable more advanced cryptographic algorithms and, therefore, a higher level of data processing security, especially in automated command and control support systems. In addition, computer modeling and simulation systems will have greater capabilities for making complex operational and organizational decisions. In the area of sensing, the implementation of quantum sensors, characterized by much higher sensitivity than classical sensors, is expected. Thanks to such use, it will be possible to design magnetic, acoustic and gravitational sensors with enhanced capabilities of detecting objects – e.g., submarines, unmanned air systems of low classes. As a part of navigation and time provision systems, quantum technologies will ensure continuity of data provision in difficult operational environments – e.g., under the water surface or in space.

In the longer term (2020-2040), which is currently the R&D phase, the potential for using quantum technologies in several areas is estimated. In the area of sensing, gravitational and magnetic sensors will be used. Precise magnetic field measurements can be used to locate submarines by maritime patrol aircraft using Magnetic Anomaly Detection (MAD) devices. Currently, the use of such devices in unmanned systems constitutes a problem because of their large mass and size. The development of quantum technology may solve the existing problem, significantly reducing the mass and size of such devices. Unmanned aerial systems, due to their advantages – long flight duration and the possibility of swarm cooperation, provide a very good concept for continuous monitoring of areas and even detection of underground structures – tunnels and bunkers. Another area of quantum technology use is the construction of georeferenced maps of gravitational and magnetic anomalies, especially in more demanding environments – e.g., in the area of space or underwater environment.

In terms of PNT (Positioning, Navigation and Timing) systems, there are two main development directions led by NATO. The first one assumes providing this type of data on the basis of reception of new generation GPS signals. The second development direction assumes the use of inertial systems – ultra-precise inertial navigation based on inertial sensors, mainly accelerometers and gyroscopes (Kwon & Jekeli, 2005). The first assumed direction is limited by increasing levels of interference – especially jamming and spoofing (Bielawski, 2020). On the other hand, quantum technologies will dramatically increase the level of operational safety of satellite navigation systems (NATO Science & Technology Organization, 2020).

6. Development of Space Technology and Hypersonic Capabilities

Currently, the NATO alliance is developing five core space capabilities: Position, Navigation, Time (PNT), Integrated Tactical Warning and Threat Assessment, Environmental Monitoring, Communications, Intelligence, Surveillance and Reconnaissance (Table 1).

Table 1. Currently developed NATO capabilities in the area of space (Filling the Vacuum. A Framework for a NATO Space Policy, 2012, p. 2)

Space Capability	NATO Use and Effects
Position, Navigation, Time (PNT) & Velocity	Precision Strike Force Navigation Support to Personnel Recovery (PR)/Combat Search and Rescue (CSAR) Network Timing
Integrated Tactical Warning and Threat Assessment	Force Protection Attribution Missile Warning
Environmental Monitoring	Mission Planning Munitions Selection Weather Forecasting
Communications	Command and Control Unmanned Aerial Vehicle Ops Beyond-the-Horizon communications
Intelligence, Surveillance and Reconnaissance	Coverage of Operation Execution (in the operations center) Battle Damage Assessment (BDA) Intelligence Targeting

Tasks so defined are possible to implement through satellites. Currently, there is a clear trend to use so-called small satellites, which are objects with a mass of less than 500 kg. This trend is mainly dictated by economic considerations, as well as faster preparation and launching of such objects into space. In addition, mini satellites reduce the risk of damage to an expensive object. Connecting them in constellations gives additional benefits in the form of performing tasks with greater resolution and efficiency. Small satellites are capable of complementing their full-sized counterparts for less demanding tasks, such as carrying a relatively small mass of payloads. They can operate individually, in constellations and swarms, as well as in autonomous mode – for missions of greater complexity. Analyzing the NATO operational capabilities using satellites, it is important to note their increasing developmental trends. Reports (Garrity & Husar, 2021) show that there are more than 2,000 satellites in space today, 15% of which perform strictly military tasks. Furthermore, the number of satellites is expected to increase five-fold by 2030 (NATO Science & Technology Organization, 2020).

It is estimated that the operation of satellites will be supported by analytical tools and sensors, the task of which will be to acquire various types of information. It is likely that communication between these space infrastructure elements will be provided by the optical two-way space communication system currently being developed and tested (Bielawski & Radomska, 2020). Additional sources will also include high-quality data acquired through Electronic Signals Intelligence (ELINT) and through Measurement and Signature Intelligence (MASINT) reconnaissance, as well as using hyperspectral images.

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Hypersonic means represent another developmental direction for NATO. Currently, conducting research on hypersonic technology concerns countries with highly developed research and development potential. The world leaders remain China, Russia, the United States, and other state actors: the United Kingdom, France, Japan, and Australia (Kulik, 2020).

In military applications, hypersonic objects are expected to perform two groups of tasks. The first is to conduct reconnaissance (ISR tasks), while the second is to implement deep high-kinetic (high-energy) combat strikes of an operational nature, especially in the first conflict phase. In this way, it will be possible to attack high-priority enemy targets, executed in a short time, using the element of surprise. Another developmental concept assumes their use as interceptors of enemy ballistic means (Czajkowski, 2021). It should be noted here that due to their specificity – high speed and maneuverability, hypersonic means are difficult to detect and track by current radar measures. Therefore, their kinetic neutralization is also highly difficult. Early developmental concepts indicate that electromagnetic means, hypersonic rail guns, jammers, and kinetic means deployed in space will constitute suitable means of neutralizing such threats.

The development of hypersonic means is related to numerous problems, the solution of which is currently under investigation. The subject of research is new mechanically and thermally resistant structural materials which can withstand high temperatures (on the surface, the temperature reaches about 1000°C). In the area of detection and tracking of objects, solutions are sought based on a system of sensors deployed both on the surface of the earth and in space. The greater efficiency of this system is to be ensured by the fusion and comparison of data.

7. Development of Biotechnology & Human Enhancement

Biotechnologies that aim to enhance human capabilities (physiological, cognitive, and social functions) have become an area of interest for NATO. They are currently focused on four research directions. The first is bioinformatics and biosensors. These activities include the development of in vitro and ex vitro sensors, medical imaging and quantum biology. Another direction is human augmentation. Here, research is conducted on mixed reality, virtual reality, social networks, robotics, AI, prosthetics, exoskeletons (Batkuldinova et al., 2021), neuro-electronics, rehabilitation, neuroscience, robotics, teleoperations, autonomy, cognitive performance, computational, artificial intelligence, trusted autonomy, perceptual enhancements. The third direction of biotechnology development concerns Medical Countermeasures and Bio-medical technologies. Scientific investigations are conducted here on the identification of Chemical Biological Radiological Nuclear (CBRN) threats, counter-measures and detection, personalized medicine, biomarkers, bio-engineering, supplements, nutrition, physiology, resilience, and stress resistance. The fourth direction of biotechnology development by NATO is Synthetic Biology. There are ongoing works on techniques such as Genetic engineering, DNA sequencing and exploitation, bio-manufacturing, modified microbiome, and living sensors (NATO Science & Technology Organization, 2020).

In terms of the development aspect related to biotechnology, currently, there is a dynamic development of biomedical sensors/biosensors – devices containing a sensing system based on biologically active particles (Vigneshvar et al., 2016). They are used to measure human biological processes (immunological, thermal, pressure, etc.). Their advantage is that they can measure human physiological parameters continuously and non-invasively, the results of which can be processed and provided to the recipient in real-time. In addition, they are small devices with relatively low costs. They may find widespread military applications, examples of which include "smart" clothing with embedded sensors for CBRN threat detection, active glucose meters, silicon photonic biosensors, and fast-applying "tattoos" for monitoring physiological or cognitive stress. A novelty in the field of biomedical sensors (wearable sensors) are devices capable of collecting medical information from human saliva and sweat. On their basis, a person's psychophysical state and stress level can be assessed (Seshadri et al., 2019). Implementing biomedical sensor technology is a key area of scientific research activity to protect soldiers, affecting their performance (Geiss, 2016) and survival. Their use will allow not only the monitoring of medical parameters of a single soldier but also a group of soldiers – a subunit.

Currently, further challenges in the field of biosensors are two developmental directions. The first concerns the possibility of obtaining data from human blood. One of the conceptual solutions that provide possibilities for such analysis is the development of biomarkers along with patches equipped with micro-needles. The second direction is related to acquiring the so-called neurocognitive data concerning brain functions. From a military point of view, they are of great importance. On their basis, it is possible to determine the ability to make decisions, remember information, maintain high alertness and the way of reacting to external stimuli, as well as human performance. Currently, real-time cognitive data can only be acquired in laboratory conditions because they are not designed for activities requiring intensive movement (Emmanuel-Aviña, 2018).

In addition to the measurement equipment – sensors – an important issue is the way of processing the acquired data. The challenge is a system for developing a statistical model for continuous analysis of human physiological data. An example is the Presymptomatic Agent Exposure Detection (PRESAGED) algorithm developed at MIT Lincoln Laboratory, the U.S. Army Medical Research Institute of Infectious Diseases, and the National Institutes of Health Integrated Research Facility. Its purpose, based on acquired data, is to estimate the probability of a subject's exposure to pathogens – viruses and bacteria, as well as their early detection before the onset of symptoms (e.g., the ability to detect infection three days before the onset of fever). Analytically, using the PRESAGED algorithm will reduce infections by 44% (Ryan, 2018). Such a good practice aims to reduce pandemics (Kołodziejczak, 2020) through self-control and self-isolation. Another advantage of the developed algorithm is the so-called quarantine-on-alert. It provides an early warning system, alerting individuals to sources of infection. The main benefit is to isolate potentially infected people from the rest of the population and to minimize costs for the government or companies in case of mass infections or pandemics.

8. Conclusions

Based on the research conducted, several general conclusions can be drawn:

1. NATO's development of Big Data will contribute to the development of threat detection, recognition and identification capabilities. For this purpose, smart textiles, and molecular and nanoscale sensors will be used. The second development direction will be the use of Big Data in radar systems – over-the-horizon (OTH) airspace surveillance and quantum detection. These techniques will allow for increasing the detection range of airborne objects. An additional source of information will be the possibility of fusion from different receptors, contributing to the increased reliability of acquired information.
2. In terms of artificial intelligence, it is expected to be used for operational autonomy, battlefield robotization, as well as fire control. The second defined development direction is intelligence analysis. As a part of these undertakings, it will be possible to collect, process and disseminate information on targeted objects.
3. The area of autonomy in NATO will be used in various domains – maritime, air and cyber. Using it for more effective sea mine fighting and submarine detection operations will be possible. Autonomy can be used to coordinate and conduct military operations by swarms of unmanned aerial systems, thus increasing their effective use and accomplishing more tasks. In the cyber domain, autonomous systems will provide a good tool for the identification and diagnosis of network threats.
4. Quantum technologies will contribute to the construction of smaller and lighter devices (sensors), which will be used in reconnaissance activities. Thanks to them and the use of unmanned aerial systems, constant reconnaissance will be possible, especially in demanding combat environments, such as space or under the ground. In addition to these quite important capabilities from the NATO point of view, there is the possibility of continuous provision of PNT services and reduction of vulnerability of these systems to jamming and spoofing techniques. This will increase the security of conducting military missions.
5. In terms of space technology, the use of small satellites operating individually, in constellations or autonomously is expected. They will be mainly responsible for ELINT electronic intelligence tasks and MASINT measurement and reconnaissance. As regards hypersonic objects, two development directions have been defined in NATO – they can be used as a combat asset and a tool for ISR (Intelligence, Surveillance, and Reconnaissance) tasks.
6. Biotechnology development by NATO is mainly focused on the research and development of biosensors. It will become a suitable tool for measuring and monitoring human biological processes and physiological parameters. Thus, it will allow for estimating the stress level, the ability to make decisions, the ability to analyze information, as well as the performance of both a single soldier and a group – a subunit.

Declaration of interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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