OPEN Publications

ISSN 2957-7160 (Online)

ISSN 2957-7799 (Print)

What Artificial Intelligence Offers to the Air C2 Domain?

Volume 7 I Number 5 I Summer 2022

OPEN Publications (2022)

"What Artificial Intelligence offers to the Air C2 domain?"

Contributing Author	Dr Wolfgang Koch, Fellow IEEE Fraunhofer Institute for Communication, Information Processing and Ergonomics FKIE University of Bonn, Institute of Informatics IV, Germany
OPEN Capability Leader	Col Geert Marien
OPEN Managing Editor	Mr Oke Thorngren
OPEN Operations Manager	Col Georgios Kotas
Action Officer	LtC David Casado
OPEN Editorial Review Board	LtC Jacob Hansen LtC Stig Frankrig LtC Faruk Akkaya LtC John Gray SGM Neculai Arghire Mr Ian Birdwell

Let us know your thoughts on

" What Artificial Intelligence offers to the Air C2 domain?"

by emailing us at:

editor@openpublications.org

Disclaimer

What Artificial Intelligence offers to the Air C2 domain

Executive Summary

Artificially intelligent automation provides new types of machines that enhance the perceptive mind and the active will of persons, who alone are capable to perceive intelligently and to act autonomously in a proper sense.

- *Cognitive* machines fuse massive streams of sensor, observer, context, and mission data for producing comprehensive situation pictures, the basis for conscious human cognition to plan, perceive, act, and assess effects appropriately.
- *Volitive* machines transform overall decisions of deliberate and responsible human volition into chains of automatically executed commands for data acquisition, sub-system control, and achieving effects on objects of interest.

Cognitive and volitive assistance of this type will enable air commanders to remain capable of acting in complex situations with spatially distributed assets and on short time scales. For this reason, NATO's future Air Command and Control (AirC2) capabilities critically depend on artificially intelligent automation for knowledge development, planning, execution, and operations assessment.[1] In the digital age, OODA loops to Observe, Orient, Decide, and Act at various stages are vastly accelerated and to be executed 'at machine speed'[2] in a network-centric and collaborative way.

NATO's competitors in a multipolar word effectively push 'Artificial Intelligence' and 'Autonomy' identified as Science & Technology Trends by NATO's Chief Scientist.[3] Moreover and different from previous military innovations, civilian domains mainly drive the rapidly evolving research and development in this branch of systems engineering if measured by the investments made.

With the advent of artificially intelligent automation, NATO needs to review its AirC2 capabilities, which integrate air mission/traffic control and air combat management with multi/all-domain awareness and operations as well as functionalities such as decision support for targeting cycles and Manned-unManned-Teaming (MuM-T). To this end, we raise awareness within the NATO community on how cognitive and volitive machines will support air commanders and staffs from the initial planning stage to the execution and assessment phases of future air operations.

Our discussion of artificially intelligent automation for AirC2 results in three recommendations and seven key results addressing the algorithms needed, the data to be processed, the programming

---

[1] *NATO Standard AJP-3.3 – Allied Joint Doctrine for Air and Space Operations.* NATO: NSO, Apr 2016, B.1. Online: https://www.japcc.org/wp-content/uploads/AJP-3.3-EDB-V1-E.pdf.

[2] Sauer, Frank. "Stepping back from the brink: Why multilateral regulation of autonomy in weapons systems is difficult, yet imperative and feasible." *International Review of the Red Cross* 102.913 (March 2020): 235–259. Online: https://international-review.icrc.org/sites/default/files/reviews-pdf/2021-03/stepping-back-from-brink-regulation-of-autonomous-weapons-systems-913.pdf.

[3] Reding, Dale F., and Eaton, Jackie, eds. *Science & Technology Trends 2020-2040. Exploring the S&T Edge.* Brussels, Belgium: NATO STO, 2020, App B, C. Online: https://www.nato.int/nato_static_fl2014/assets/pdf/2020/4/pdf/190422-ST_Tech_Trends_Report_2020-2040.pdf.

skills required, the computing devices to be used, the inevitable anthropocentric design, the reviewing of R&D efforts necessary, and the integration of other military dimensions.

“Firmly confident in his better inner knowledge, the military leader must stand like the rock where the wave breaks,” observed Carl von Clausewitz (1780–1831), the Prussian general and military theorist who stressed the moral, psychological, and political aspects of war.[4] Thus, artificially intelligent automation requires the ethos of digitally educated air commanders and staffs. They do not need to know how to design and program artificially intelligent and automated AirC2 systems, but to assess their strengths and weaknesses, risks, and opportunities. The associated digital morality and competence is teachable. It addresses a key question of the soldierly ethos, which is aggravated by artificially intelligent automation in AirC2, but is not fundamentally new.

AI and Automation

In future air defence and combat, fighter aircraft and Unmanned Aerial Systems (UAS) form comprehensively networked system of systems. As loyal wingmen, cooperating multiple-sensor, multiple-effector UAS protect the pilots or assets and execute reconnaissance or combat missions with electronic or kinetic impact, whereas satellites, airborne early warning, inflight refueling, or air transporting will be integrated. The core infrastructure are air combat clouds, symbolically visualized in Figure 1, which makes relevant information available to all actors on a mission in real time and provides means for adaptive resources management ‘at machine speed’. In the digital age, information superiority in complex situations and decision dominance even at very short time scales decide between success and failure of a mission.

Figure 1. Air Combat Cloud enable artificially intelligent automation for Manned-unManned Teaming in combat and reconnaissance missions. © Fraunhofer FKIE.

[4] von Clausewitz, Carl. *Vom Kriege* [On War]. 11th ed. Hamburg, Germany: Nikol, 2018, I.6, 96.

In accordance with the German Military Aviation Strategy, to take an example,[5] the responsibility of human decision makers is pivotal for AirC2 scenarios. For this reason, the architecture of future AirC2 systems will have to facilitate its responsible use by human decision makers. Artificially intelligent automation is crucial since it enables complexity management and responsible action by cognitive and volitive assistance. In parallel, realistic simulations accompanying the technological development from the beginning have to ensure that comprehensive ethical and legal compliance is not at the expense of effectiveness in air defence and combat.

We here use the term 'Artificial Intelligence' (AI) in a sense that does not only comprise machine or deep learning, e.g., but a whole 'world' of data-driven and model-based algorithms, including approaches to Bayesian learning, game theory, and adaptive resources management.[6]

As illustrated in Figure 2, this 'World of Algorithms', realized by the art and craft of programming and enabled by qualitatively and quantitatively appropriate testing and training data, drive a data processing cycle that starts from elementary signals, measurements, and observer reports collected from multiple and heterogeneous sources. We call 'AI' the process of fusing these streams of mass data and context knowledge that provides pieces of mission-relevant information at several levels, which are integrated into comprehensive and near real-time situation pictures.

Figure 2. Cognitive and volitive assistance for the intelligent mind and autonomous will of responsibly acting air commanders. © Fraunhofer FKIE.

On their basis, air commanders and staffs become aware of the current situation in a challenging environment and the status of the mission. Human decision-making for acting according to the

---

[5] *Militärische Luftfahrtstrategie 2016* [Military Aviation Strategy]. Berlin, Germany: BMVg, Jan 19, 2016, 23. Online: https://www.bmvg.de/resource/blob/11504/3e76c83b114f3d151393f115e88f1ffb/c-19-01-16-download-verteidigungsministerium-veroeffentlichtmilitaerische-luftfahrtstrategie-data.pdf.

[6] Koch, Wolfgang. *Tracking and Sensor Data Fusion—Methodological Framework and Selected Applications.* Heidelberg: Springer, Mathematical Engineering Series, 2014.

ends of the mission to be achieved are made at different levels of abstraction and degrees of detail. Algorithms transform acts of will into partially or fully automated command sequences for controlling networking platforms, multifunctional sensors, communications, and effectors.

Algorithms for harvesting information from data fusion and collecting data via adaptive resources management belong to the methodological core of cognitive and volitive machines for AirC2 that assist the intelligent minds and autonomous wills of air commanders and staffs. They exploit sophisticated methods of applied mathematics and run on powerful computing devices, where quantum computing may become a game changer. The concepts of mind and will that are to be assisted and, therefore, of consciousness and responsibility bring human beings as persons into view that are "somebody" and not "something," and open up the ethical dimensions of AirC2.

To discuss this complex field with its various facets, we let us guide by the seven pillars of artificially intelligent automation, originally sketched by USAF General John Hyten (b.1959), Vice Chairman of the US Joint Chiefs of Staff that we are adapting appropriately.[7] The resulting 'Pillars of AirC2' are 'World of Algorithms', 'Data, Data, and Data', 'Art of Programming', 'Computing Devices', 'Anthropocentrism', 'Push, Pull, Realize', and 'Joint and Combined' as displayed in Figure 3.

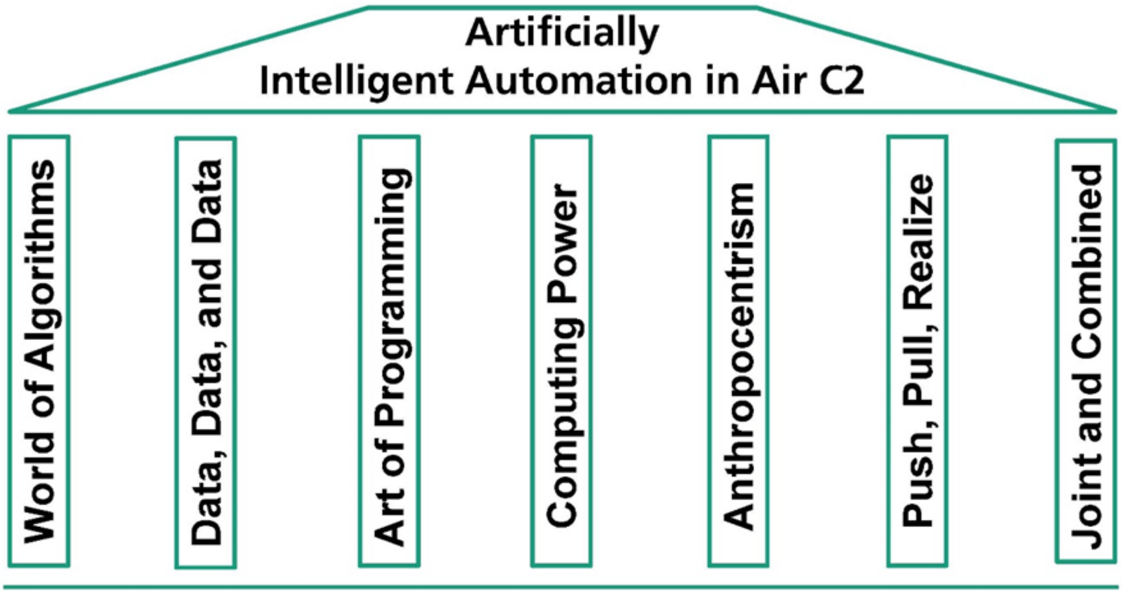

Figure 3. Seven pillars of artificially intelligent automation in the Air Command and Control (AirC2) domain. © Fraunhofer FKIE.

Along this path and with a view on national allies' policies and developments in AI as well as on the worldwide scientific AI community, we address different perspectives of future AirC2, including decision-making and MuM-T. Moreover, the several integration aspects of artificially intelligent automation into the AirC2 architecture, including potential redefinitions of notions and concepts, and its consequences for the Air Tasking Order (ATO) as well as for the various targeting cycles will become visible. The intended impact of this paper on the NATO community is to provide infor-

[7] Hyten, John E. "Remarks to the joint artificial intelligence symposium." Washington DC, USA: DOD, Sep 9, 2020. Online : https://www.defense.gov/Newsroom/Transcripts/Transcript/Article/2344135/remarks-by-general-john-e-hyten-to-thejoint-artificial-intelligence-symposium/.

mation on the benefits of artificially intelligent automation in the AirC2 domain, to raise the awareness among the NATO member states, and to support the adaptation of AI-based technologies by the Alliance in general. We conclude by giving three recommendations and summarize the discussion in seven key results related to the seven pillars mentioned.

1 World of Algorithms

Artificially intelligent automation enables air commanders and staffs to acquire knowledge about threats, combatants, uninvolved parties, and options for action in the various operational theaters. In particular, the consideration multi- or even all-domain operations will become increasingly important for AirC2, i.e. Ground, Sea, Space, and Cyber. At the same time, AI-enhanced situational awareness and precision targeting can minimize risks for friendly forces,[8] the civil population, the infrastructure, the environment, etc. Cognitive and volitive assistance may thus help to master complex tasks in Air C2 more adequately and to balance human subjectivities. Moreover, the physical presence of human beings is thus increasingly dispensable in dangerous air situations. To sum up, algorithms that drive artificially intelligent automation in AirC2 are crucial to

- evaluate imperfect and incomplete mass data;
- to fuse context knowledge with current data streams;
- to fuse complementary and heterogeneous sources;
- to estimate the plausibility of the information content;
- to enable manned–unmanned teaming and action;
- to enable ethical, legal, and societal compliance.

As indicated in Figure 4, the question of "what" is decisive for situational awareness. Detection algorithms inform about the 'existence' of relevant objects and phenomena, while classification algorithms provide information about their properties, i.e., their 'essence' and intents. Important building blocks are furthermore algorithms that infer object interrelations. Finally, situation pictures have to indicate decision relevance, such as estimated threat levels and the status of own resources and countermeasures.

---

[8] Long, Jill A. "The problem with precision: Managing expectations for air power." *Master of Strategic Studies*. Carlisle Barracks, PA, USA: US Army War College, 2013, 28. Online: https://apps.dtic.mil/dtic/tr/fulltext/u2/a589415.pdf.

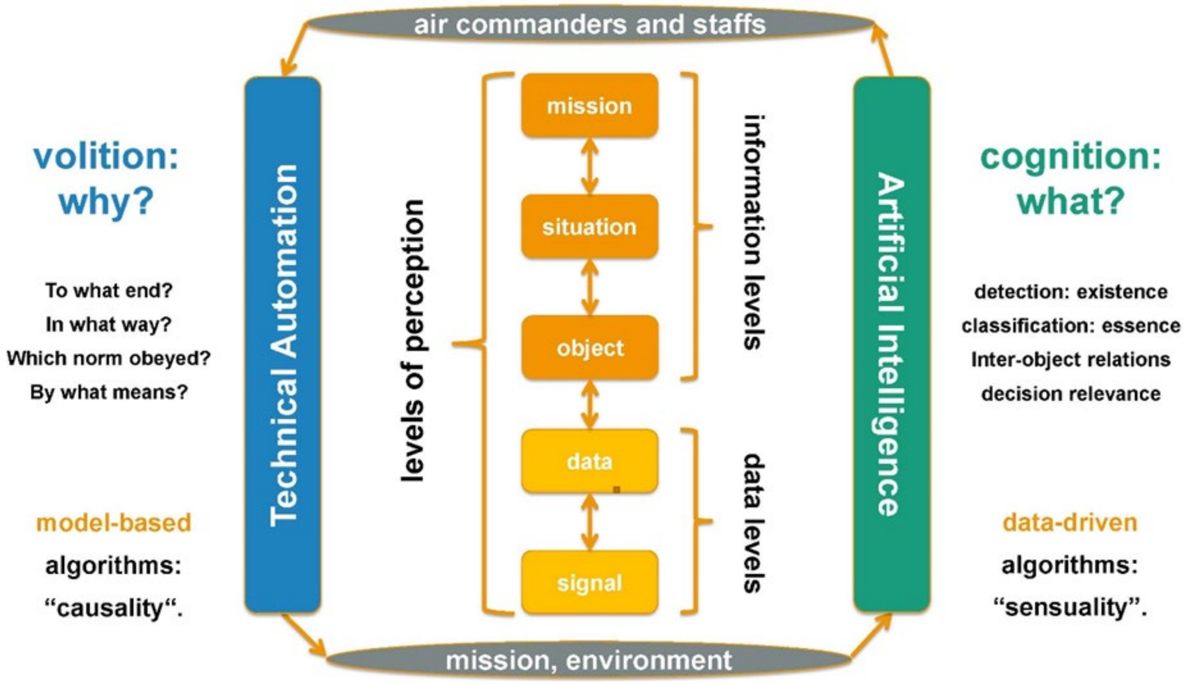

Figure 4. Levels of AI-assisted perception and action for command and control, ISR, engagement, and impact assessment. © Fraunhofer FKIE.

The situation picture as well as statements about its limitations and gaps, on the one hand, and the actual situation on the other, must mutually correspond. This implies a concept of ‘truth’ and its most elementary definition: Truth consists in the equivalence between the situational awareness picture and the situation itself. We may distinguish between the *logical* truth of the picture and its *ergonomic* truth, in which it corresponds to the tasks, roles, and abilities of the Air Commander.

Algorithmically driven automation translates the intentions of the decision maker into complex cause-effect chains to manage assets, such as multifunctional sensors, mobile platforms, communication links, and electronic or kinetic effectors. The question of “why” to achieve an effect is crucial for the algorithm design. According to the four ways of answering to why-questions, the intentions correspond to the final cause, usually specified by performance parameters characterizing the intended effect. The effective cause indicates by which concrete algorithms the effect is to be achieved. The formal cause answers the question, according to which rules this should happen. Finally, the material cause indicates necessary resources to be used with their respective properties.

The close link between the formal and the final cause corresponds to the principle that military ends are to be achieved according to the Rules of Engagement (RoE). Mission preparation corresponds to the link between material and formal cause. Finally, impact assessment determines the extent to which the final cause of the military action has actually been achieved and is basic for further action.

In general, we distinguish data-driven from model-based algorithms. The first family, for which deep learning is exemplary, corresponds to intuitive sensory perception—‘What do I see?’. The second family, in the sense of Bayesian reasoning, enables rational causal action—‘What do I do to what end?’.

Figure 5 is in a sense a 'map' of the 'World of Algorithms' that drive artificially intelligent automation in AirC2, where we distinguish between five levels of perception. The first two levels, determined by received signals, measurements, or human observer messages long with the corresponding signal or language processing, are data levels and usually hidden from military decision makers. For them, the three subsequent information levels are more relevant. They refer first to the individual objects, second to the situation with information about the interrelation between the objects, and third to the mission itself, i.e., the underlying situation including the decision maker who wants to act in it according to his or her resources.

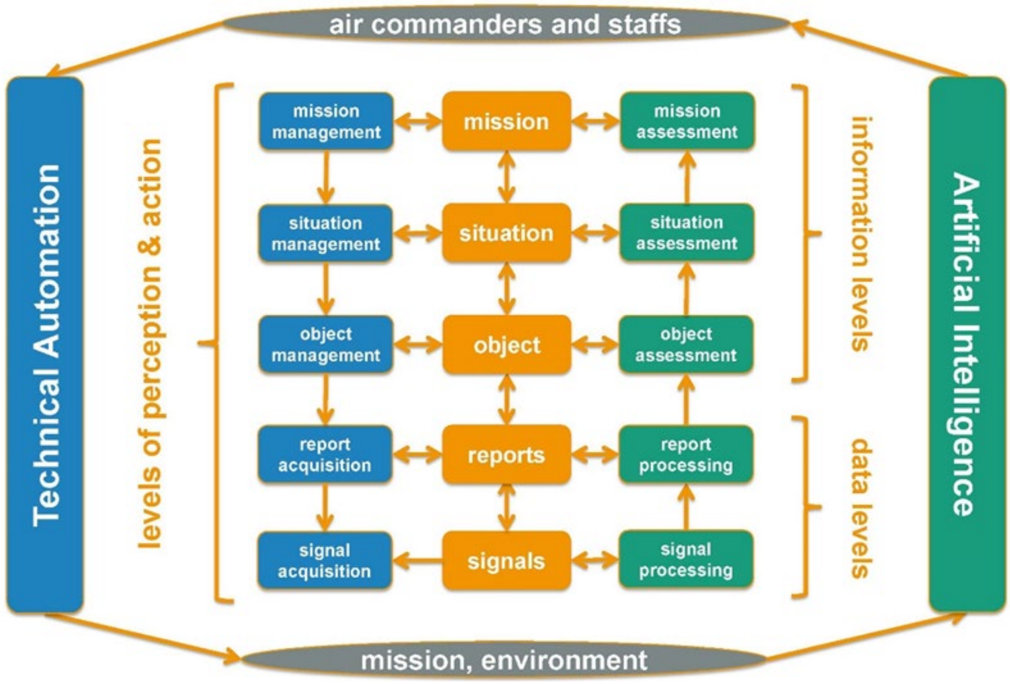

Figure 5. Map of the algorithms that drive artificially intelligent automation in AirC2 with interrelated OODA loops on every level. © Fraunhofer FKIE.

2 Data, Data, and Data

Distributed cross-platform AirC2 requires interoperable and modular AI-enabled capabilities that fuse heterogeneous data from multiple sources in a wide variety of data formats that are not always precisely known or may even be corrupted. For this reason, the 'World of Data' that complements the 'World of Algorithms' needs to be carefully analyzed. Seen from a more abstract perspective, we distinguish between

- data required for the development, testing, and certification of algorithms,
- data that we need to train or properly re-train data-driven algorithms, and
- data to be processed during a mission, i.e. sensor, context, and mission data.

Future AirC2 systems will therefore need an informational infrastructure, which collects, aligns, registers, verifies, organizes, evaluates, provides bookkeeping, and securely distributes these three types of data in decentralized air combat clouds. This informational and communicative backbone for data that feed algorithms ensure scalable data management and forms the very basis for a standardised, interoperable, and robust use of the various algorithms along with the models underlying them. Moreover, this infrastructure is the prerequisite for reproducibility, verification and traceability as well as efficiency and effectiveness. Otherwise, at least elements of it were to be developed separately for each individual capability and subsystem, an approach that is not only inefficient, but may facilitate hostile cyber attacks and prevent interoperability.

Since decentralization and artificially intelligent automation necessarily implies vulnerability, data integrity is fundamental to AirC2. Among the reasons for lost integrity are unintended malfunction of sensors, programming errors, misuse of testing and training data, or data incest. Moreover, AI algorithms always generate artifacts from data that do not exist in reality, or have “blind spots,” i.e., do not show what is actually there. In naive systems, lost integrity easily turns data fusion into confusion and resources management into mismanagement.

In a military environment, also hostile intervention at various levels is a hot topic, where adversaries take over sensors or subsystems, which then produce deceptive data or unwanted action. As indicated in figure 6, own systems need protection against attacks from the electromagnetic spectrum and the cyber space as well as from adversarial attacks against the AI used, while strategies to attack enemy systems in this way need to be developed.

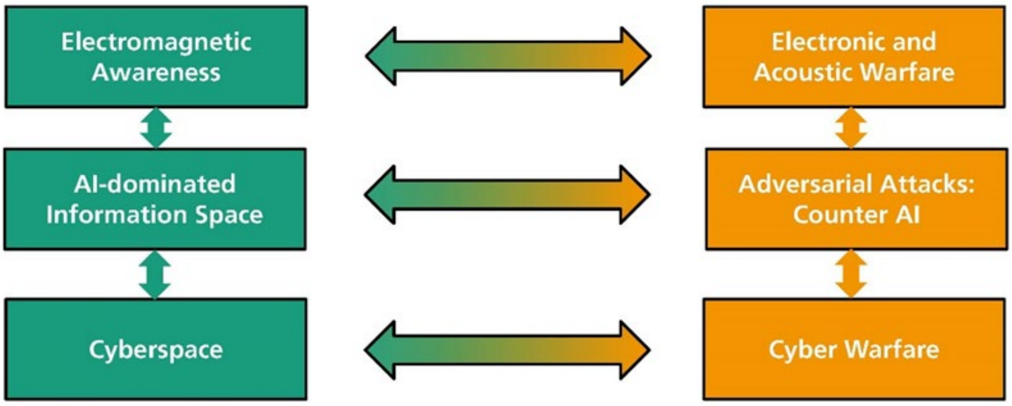

Figure 6. Preserving own and attacking the adversaries’ data integrity: a key function in air combat clouds. © Fraunhofer FKIE.

Mature cognitive and volitive machines for AirC2 comprise detection of such deficits, which is the basis for resilience toward hostile interference and deception. Therefore, preservation of data integrity, reliable detection of violations, or testing, whether unavoidable deficits at least correspond to the statistical specifications made, will be a central functionality of the informational backbone previously addressed.

As an example, let us consider neural networks for object classification that, seen from an abstract point of view, assign an input to an output. The output describes what an input image, for example, should ‘mean’ for the user. Characteristic of such functions is their extremely large number of internal degrees of freedom, tunable numerical values. In a so-called ‘training phase,’ they are adjusted by ‘telling’ the neural network what a particular input actually ‘means,’ e.g., by ‘understood’ examples. The ‘labeling’ of training data requires human understanding. If training has been ‘long enough,' the network is offered an arbitrary input and the output is considered the recognized 'what,' i.e., the 'meaning' of the input. Neural networks are, thus, essentially function approximators. Whoever calls massive offering of interpolation points 'learning' may awaken erroneous associations in non-specialists.

As it turns out, however, only a few pixels in an input image, for example, need to be changed in a specific way to completely mislead even well-trained networks. A neural network, deceived by such "poisonous noise," may misrecognize a panda bear, for example, which appears unchanged to humans, as a gibbon monkey and 'feels' certain in its judgment.[9] The military relevance of this discovery is obvious. Attack systems against AI systems have already been developed; own AI systems are to be hardened against such "adversarial attacks." A situation occurs as in electronic warfare where electronic measures call for countermeasures, these for counter–countermeasures and so on. In addition, appropriately representative training data for data-driven algorithms are for most militarily relevant applications unavailable in sufficient amount.

3 Art of Programming

Among the "100 or so Books that shaped a Century of Science"[10] is the famous, but still unfinished series *The Art of Computer Programming*,[11] written by Donald Knuth (b. 1938), one of the most influential pioneers of computer science, recipient of the Turing Award in 1974.[12] The distinction between the 'World of Algorithms' and the 'Art of Programming' reflects the difference between scientists, who provide problem solutions in the form of algorithms on a mathematical basis, and engineers according to the original meaning of the Latin word *ingenium*, i.e. as men of talented art.

This observation has direct consequences for realizing AI-driven systems in proper organizational structures. While it may be a difficult scientific task to find a basic algorithm for solving a problem in AirC2, it is usually only a matter of diligence to understand it at last. Bringing understood algorithms 'to life' in complex software systems, however, is an art, perhaps a craft. The 'Art of Programming' is typically achieved by comparatively small and 'conspiratorial' teams of programmers, who know exactly what they are doing and have an inner and passionate understanding of the problem to be solved, of the algorithms available, the data, the models, and the computing devices. These core teams, maybe in AI start-up companies, need to be embedded in larger software engineering units that integrate "artfully crafted" AI core systems into the wider context of AirC2 systems.

This situation is openly described by General Hyten, i.e. from the perspective of a country which enormously invests in AI for defence applications. "When you look at software in the Department of Defense, oh my gosh, we develop software in archaic, ridiculous, 20th-century ways that never worked," Hyten observes phenomena that may be existing in other NATO member nations as well.

[9] Goodfellow, Ian et al. "Explaining and harnessing adversarial examples." *Proc. International Conference on Learning Representations*. San Diego, CA, USA, 2015, 1-11. Online: https://arxiv.org/abs/1412.6572.
[10] Morrison, Philip and Phylis. "100 or so Books that shaped a Century of Science." *American Scientist* 87.6 (Nov-Dec 1999): 542–53.
[11] Knuth, Donald E. *The Art of Computer Programming.* 4 vols. 3rd ed. Reading, MA, USA: Addison-Wesley, 2011.
[12] "Donald ('Don') Ervin Knuth." *A. M. Turing Award.* New York, NY, USA: ACM, 1974. Online: https://amturing.acm.org/award_winners/knuth_1013846.cfm.

“If you go where software development is a key piece, our nation moves unbelievably fast. If you go in the Department of Defense, unbelievably slow. Unbelievably slow. How to change this? […] If we continue to do business the way we’ve been doing, we will not be successful.”[13]

For this reason, everyone, who is in charge to develop artificially intelligent automation for AirC2 should consider the establishment of an ‘ecosystem’ of AI players from various and even non-military domains, i.e. ‘innovation incubators’, that are horizontally complementing capabilities of established companies providing, platforms, sensors, communications and electronic warfare systems, or weaponry.

Another example, where artful skills of programmers are crucial, is modeling, since data for AirC2 never meet ideal expectations, they are always imperfect, inaccurate, ambiguous, unresolved, corrupted or deceptive, difficult to be formalized, or partly even contradictory. Artfully crafted models, however, to be exploited by algorithms produce reliable information even on an imperfect data basis. Moreover, an ‘art’ is also the realization of effective model-based algorithms that allow logical reasoning also in case of uncertainty, that uncover probable cause-effect chains, deliver probabilistic assessments of the estimated pieces of information provided, and explicitly allow the integration of context and expert knowledge. In militarily relevant cases, however, it may well be the case that the required models are not available or too complex to be dealt with efficiently. The proper choice of training data for training or re-training data-driven algorithms and even simulating such training data properly, if real data are unavailable in sufficient quantity and quality, is critical and often an ‘art’ in itself.

The basis for certification and qualification of artificially intelligent automation is in many cases provided by ‘artful programming’ and inspired choices in the software design that require both, in-depth and holistic understanding. In this spirit, robust and resilient AirC2 systems will comprise data-driven and model-based algorithms, where the data-driven subsystems could be ‘contained’ by model-based reasoning—‘AI in the Box’. Similar considerations are valid for achieving predictable system properties, insensitivity to unknown effects, adaptivity to variable usage contexts, and graceful degradation. Moreover, statistical testability as well as explainability are essential prerequisites for critical components, along with compliance to a code of conduct to be guaranteed by responsible systems design.

4 Computing Devices

In air combat clouds, all elements such as flying platforms, sensors, as well as communications, electronic warfare, or weapon systems are essentially computers themselves. Ubiquitous distributed computing will, thus, be an essential characteristic in future AirC2. Important problems of ‘classical computing’, too complex to be discussed here, are related to secure data transmission in combat clouds, especially when quantum de-encryption will be available, as an example. Other pressing questions are: “Doesn’t the cyber threat contradict data centricity and digitalisation in the future at all?” or “How to integrate sensor signal processing, target tracking and classification, as well as data fusion ‘at the edge’ on a single chip?”

[13] Hyten.

In view of AirC2 systems of the future, we here rather address quantum algorithms for data fusion and resources assignment that may become game changers as soon as quantum processing kernels embedded in hybrid processing architectures with classical processors will exist.

While the military potential of emerging quantum communications, quantum sensing, and quantum computers directly apply quantum physics, quantum algorithms, as considered here, do not exploit quantum physical phenomena as such, but rather use the sophisticated mathematical framework and numerical methods of quantum physics to deal with 'uncertainty', the essence of quantum physics. This seems reasonable since for approaching fundamental uncertainty characterizing molecular, atomic, and subatomic levels, quantum physicists have developed a powerful framework.

Interestingly, there is a hidden link between the formalisms of mathematical statistics and quantum physics. Although this connection has long been known, the potential of physics-inspired quantum algorithms for data fusion has just begun to be realized with the aim to design more powerful algorithms for fusing uncertain data. This has direct military implications, since situation pictures, the very basis of military decision-making, are typically produced from uncertain data. Reasoning along these lines has already been shown to be promising.[14]

While the implementation of quantum algorithms is to be considered on classical as well as on quantum computers, the latter are anticipated as well-adapted "analog computers" for unprecedentedly fast solving data fusion problems that are highly relevant to AirC2. Among them are algorithms for solving the problem of weapon target assignment[15] and of multiple target data association.[16] The class of quantum computers being referred to are "adiabatic" computers, of which the D-wave machines are currently the best-known commercial products. It is to be expected that quantum and classical computers will be coupled in creative ways to solve real problems of AirC2 synergistically.

The development of quantum computers for practical problems in AirC2 is an ongoing research activity and cannot be taken for granted. This is called (regrettably) the "quantum supremacy" problem. The potential is nonetheless real and has to be considered by the NATO community. With the advent of quantum computers in AirC2, which might become reality within the next decade, massive streams of uncertain data are expected to be fused at an unprecedented speed also by NATO's competitors. Quantum algorithms have, thus, the potential of being revolutionary game changers for obtaining information superiority and decision dominance in future AirC2 systems of systems. We anticipate the following development:

- *Short Term.* The quantum analogs for a variety of data fusion algorithms will be identified, mathematically analyzed, investigated via simulations and experiments as well as quantitatively evaluated. This is more than just 'good science' – it builds the kind of confidence in the solution and the hardware that NATO requires to achieve.

---

[14] Koch, Wolfgang. "On Indistinguishability and Antisymmetry Properties in Multiple Target Tracking." *Journal of Advances in Information Fusion* 14.2 (Dec. 2019): 199-212.

[15] Stooß, Veit, Ulmke, Martin, and Govaers, Felix. "Adiabatic Quantum Computing for Solving the Weapon Target Assignment Problem," *Proc. ISIF International Conference on Information Fusion*. Sun City, South Africa: ISIF, 2021. 1-8. Online: https://www.researchgate.net/publication/351355037_Adiabatic_Quantum_Computing_for_Solving_the_Weapon-Target_Assignment_Problem.

[16] Govaers, Felix, Stooß, Veit, and Ulmke, Martin. "Adiabatic Quantum Computing for Solving the Multi-Target Data Association Problem." *Proc. IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems.* Karlsruhe, Germany: IEEE, 2021, 1-7.

- *Medium Term.* Well-understood quantum algorithms for data fusion and resources management will be implemented and evaluated on quantum kernels and quantitatively analyzed. Situational awareness and decision support is made available in complex operational AirC2 scenarios that are intractable by classical data fusion processing.

5 Anthropocentrism

The importance of automation for the German Armed Forces, to take an example, was recognized as early as in 1957, one year after the term 'AI' was coined, when their conceptual architect wrote that thanks to automation, "human intelligence and manpower will once again be able to be deployed in the area that is appropriate human beings."[17] From this point of view, NATO's armed forces do not face fundamentally new challenges as users of AI-driven AirC2 systems, since the technological innovation has long extended the range of military perception and action.

According to high-rank documents of the German Ministry of Defense, the importance of AI does not lie "in the choice between human or artificial intelligence, but in an effective and scalable combination of human and artificial intelligence to ensure the best possible performance."[18] This statement comprises the ergonomic as well as the ethical and legal dimensions of Air C2 and forms the basis for research questions concerning ethically aligned AirC2 systems engineering and aims at fulfilling a more fundamental military requirement.

In this spirit and for the first time in Germany, an intellectual struggle over the technical implementation of ethical and legal principles accompanies a major air defense project from the outset. The goal of the working group on 'Responsible Use of New Technologies in a Future Combat Air System (FCAS)' is to operationalize ethically and legally aligned systems engineering.[19] Such efforts are necessary, since readiness to defend the NATO member nations against highly armed opponents must not only be technologically credible. Defence also has to correspond to the consciously accepted "responsibility before God and man, inspired by the determination to promote world peace as an equal partner in a united Europe," as the very first sentence of the German Constitution proclaims, to give an example.

A challenge for consistent and responsible controllability of AI in the AirC2 domain is first the ever-decreasing time available for human involvement in the decision-making process. A further problem is limited explainability and deceivability of algorithmically generated information and the automated execution of complex command chains. At least for critical functions in the targeting cycle, meaningful human control is required. According to these considerations, the following issues are pressing in Air C2 and need to be addressed by C2 systems engineering.

1. In certain applications, occasional malfunction of AI and automation may have no consequences. In AirC2, however, rigorous safety requirements must be guaranteed with all legal consequences. The military use of technically uncontrollable technology is immoral per se.

---

[17] von Baudissin, Wolf. *Soldat für den Frieden. Entwürfe für eine zeitgemäße Bundeswehr* [Soldier for Peace. Drafts for a Contemporary Bundeswehr]. München, Germany: Pieper, 1969, 174

[18] *Erster Bericht zur Digitalen Transformation* [First Report on Digital Transformation]. Berlin, Germany: BMVg, Oct 10, 2019. Online: https://www.bmvg.de/resource/blob/143248/7add8013a0617d0c6a8f4ff969dc0184/20191029-download-erster-digitalbericht-data.pdf.

[19] *The Responsible Use of New Technologies in a Future Combat Air System.* Online: www.fcas-forum.eu.

2. The notion of "meaningful human control" needs to be interpreted more broadly than the concept of "human-in/on-the-loop" suggests. More fundamental is "accountable responsibility". The use of fully automated effectors on unmanned platforms may well be justifiable, even necessary in certain situations, if the overall system is appropriately designed.

In view of these considerations, artificially intelligent automation in AirC2 poses a timeless question: How to decide 'well' according to what is recognized as 'true'? Turned into systems engineering, this leads to three other tasks dealing with responsible controllability:

1. Design cognitive machines in a way that human being are not only mentally but also emotionally able to master each situation.

2. Identify technical design principles that facilitate the responsible use of artificially intelligent automaton in AirC2 systems.

3. Guarantee that human decision makers in AirC2 have full superiority of information, decision-making, and options of action.

"All thinking is art" observed von Clausewitz. "Where the logician draws the line, where the prefixes end, there art begins".[20] For this reason, digital ethics and a corresponding ethos and morality are essential soft skills for air commanders to be built up systematically in parallel to technical excellence. Leadership philosophies and personality development plans of NATO's air forces should encourage ethical competence for designing and using AI-based AirC2 systems.

6 Push, Pull, Realize

Anyone thinking about innovative technologies for AirC2 must first define the term "innovation in defence technologies" more precisely. How do research and development, analyses and evaluations from missions, and technology demonstrations contribute not only to identifying but also realising innovation potentials? Successful research and experimentally verified technologies can only trigger innovation in AirC2 if they respond coherently to three innovation vectors:

1. *Operational added value*. New technologies realize their innovative potential only if they actually help close essential capability gaps of NATO's AirC2 air commanders and staffs, significantly expand their range of tasks, and ultimately enable them to take increased risks to fulfil these tasks, which they would not or could not otherwise expose themselves to.

2. *Concepts and procedures*. Innovative R&D results must be integrated into Concepts of Operations (CONOPS). In a continuous innovation process, on the one hand, a new technology just replaces an obsolete technology, but the processes and procedures remain largely unchanged. Disruptive innovation, on the other hand, opens up fundamentally new application possibilities, which at the same time require conceptual and organisational changes.

3. *Cultural and social acceptance*. Innovation potential can only be realized if one takes into account how air commanders and staffs think about technology, how certification bodies work, and how procurement authorities operate. Personal engagement of committed actors is crucial in this process. In addition, there must be social and political acceptance, without which the major investments in innovative technologies for AirC2 would not be feasible.

[20] von Clausewitz. II.3, 135.

Synchronous development along these innovation vectors requires a balance between technology push and concepts pull. This is particularly true for AirC2, where the quality of defence research gains its special value through consistent attention to these innovation vectors. Its innovative potential will only be truly effective, however, if realised together with the military users and the defence industry.

The key to innovative impulses from defence R&D are technology demonstrators, into which military analyses and evaluations as well as more fundamental research results flow. Overall, we do see a favourable macro environment for innovation in AirC2.

1. *Technologically.* Megatrends such as artificial intelligence, machine / deep / Bayesian learning, cognitive and multifunctional sensor technology, data fusion engines, unmanned mobile systems, automation in its various degrees, networking, electronic / navigation / cyber warfare, big / smart / sparse data, quantum technologies and materials are also driving the development of technologies that are beneficial for AirC2.

2. *Politically.* Precisely in the times of renewed global competition, provision for external security and defence is a political issue. In order to protect their common heritage of culture, personal freedom and the rule of law in an increasingly fragile world, NATO nations must be able "to fight at machine speed" if necessary. For this reason, digitization in defence cannot not be confined to logistics, maintenance, intelligence, surveillance, and reconnaissance, but must equally enable responsible AI-based weapons engagement.

3. *Socio-demographically.* In European societies, we are experiencing increasing support for defence R&D from the broadening approval of the population for the national armed forces, as well as the realisation that they must be fundamentally renewed at the technological level. At the same time, we are observing a generally growing need for security among the population with increasing, albeit critical, acceptance of high technology.

7 Joint and Combined

For operational reasons, the military dimensions in terms of Joint All Domain Operations (JADO) are converging and require systems for Multi-domain Command and Control (MDC2). Evidently, the informational and communicative infrastructures for future AirC2 systems are not only relevant for the air domain, but also for land, sea, space, or cyber after suitable modification. Therefore, the previous discussion is naturally embedded in a much wider framework.

More instructive than an abstract discussion in the context of this paper is an example that should conclude our discussion of the seven pillars of artificially intelligent automation for AirC2.

Figure 7 shows a convoy under attack that was stopped in an urban environment by an improvised explosive device. Coordinately operating reconnaissance fixed- and rotary-wing drones support the Forward Air Controller (FAC) by providing input data for a comprehensive situation picture, including the expected collateral damage, the basis for self-defense by commanding a combat drone. Here, artificially intelligent automation provides technical prerequisites for effective and responsible engagement with minimized risk for non-combatants. We claim that armed drones enable reliable or at least, compared to other weaponry, significantly more reliable target reconnaissance and control up to the final engagement decision.

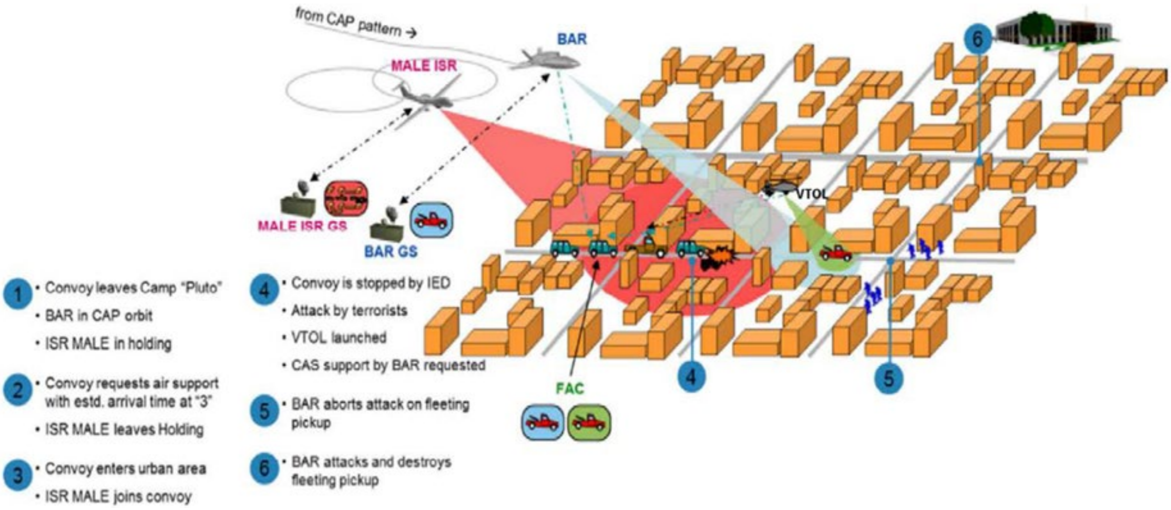

Figure 7. Coordinated reconnaissance and armed drones enable the FAC to defend against threats in compliance with the RoE. © Airbus Defence & Space.

Rules of Engagement (ROE), which do not make any tactical specifications, but define a legally binding and mission-specific framework, are important for a pre-engagement situation analysis. In compliance with legal, political, strategic, and operational requirements, they concretize the *ius in bello*, i.e., the principles of the International and Soft Law. Examples are discrimination (engagement only if targets are fully identified), proportionality (choice of threat-adequate effectors), care, and imputability to a responsible person. Evidently, RoE are to be taken into account in designing AI-based systems (RoE Compliance by Design).

In conclusion, cognitive and volitive machines enabled by artificially intelligent automation support military actors in this two-domain scenario (air and ground) to acquire comprehensive situational awareness and options for action in the challenging urban operational theater. At the same time, risks for all involved parties can be minimized.

Recommendations

For advice on technical issues arising from the use of artificially intelligent automation for AirC2, NATO has an excellent and proven instrument in the form of its Science and Technology Organisation (STO) with its various panels. We here note that the exchange between the military and scientific branches of NATO should be intensified in the interest of the operational use of the findings provided in the different working formats of NATO STO.

Since we feel encouraged to assume that a broader consent among the NATO member nations might be achieved, we are closing with some recommendations that address a certain blind spot, at least in the public perception of NATO according to the observations of the author.

1. Digital ethics and a corresponding ethos and morality should be built up systematically for responsibly using artificially intelligent automation in AirC2 and in the other military domains. In particular, such skills enable air commanders "to assess the potential and impact of digital

technologies and to manage and to lead in a digitized environment,"[21] as an official German document states. In particular, leadership philosophies and personality development instruments should encourage such competences with regard to AirC2.

2. In addition to the operational benefit of artificially intelligent automation for AirC2 in closing capability gaps, expanding the range of capabilities, and developing corresponding concepts, operational procedures, and organizational measures, ethical and legal compliance need to be achieved. Only then, cognitive and volitive assistance will become acceptable before the conscience of the individual air commanders, but also in the broader view of the Common Good of the society as such. Success in both aspects will indicate a real innovation.

3. Projects in the AirC2 domain should be accompanied from their very beginning by comprehensive analyses of technical controllability and personal accountability in a visible, transparent, and verifiable manner. Otherwise, the paradigm shifts and large material efforts associated with artificially intelligent automation would hardly be politically, societally, and financially enforceable. Of course, there will be more and less problematic AirC2 projects, implying that an exemplary approach according to these lines would be appropriate.

Key Results

Future air command and control is characterized by vastly accelerated OODA loops for decision-making at various levels. Artificially intelligent automation intends to tame the technical complexity involved and to unburden air commanders and staffs from routine or mass tasks. Decision-makers are, thus, able to focus their mental capabilities on doing what only persons can do, i.e., to consciously perceive a situation intelligently and act responsibly.

We summarize our discussion by seven results addressing the algorithms needed, the data to be processed, the programming skills required, the computing devices to be used, the inevitable anthropocentric design, the reviewing of R&D efforts necessary, and the integration of other military dimensions.

1. Rapidly evolving algorithms for harvesting information and collecting data by adaptive resources management are the methodological core of cognitive and volitive machines that assist the intelligent minds and autonomous wills of air commanders and staffs.

2. Future AirC2 systems will need an informational backbone, which collects, aligns, registers, verifies, organizes, evaluates, provides bookkeeping, and securely distributes data for testing, training/retraining, and information fusion in decentralized clouds.

3. The algorithmic core of artificially intelligent automation is to be realized by comparatively small teams of skillful programmers, who know exactly what they are doing. Standard software engineering will embed these "artfully crafted" cores in the AirC2 context.

4. Ubiquitous computing is an essential characteristic of distributed air combat clouds. Data association and resources assignment algorithms that will run on quantum processing kernels embedded in hybrid computing architectures may become game changers.

[21] *Umsetzungsstrategie ‚Digitale Bundeswehr'* [Implementation Strategy 'Digital Bundeswehr']. Berlin, Germany: BMVg, Jun 14, 2019, 209, 8. Online: https://www.bmvg.de/de/themen/ruestung/digitalisierung/umsetzungsstrategie-digitale-bundeswehr

5. The importance of AI in AirC2 does not lie in the choice between human or artificial intelligence, but in an effective and scalable combination of human and artificial intelligence to ensure the best possible performance. This comprises the ethical and legal dimension.
6. Successful research and experimentally verified artificially intelligent automation can only trigger innovation in AirC2 if it responds to the operational added value and military concepts & procedures. Moreover, it has to achieve cultural and social acceptance.
7. For operational reasons, the military dimensions are converging and require appropriate C2 systems. The informational and communicative infrastructures for future AirC2 are not only relevant for operations in the air domain, but also in the other dimensions.