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Faculty of Technological Engineering and Industrial Management

Mihai-Alin MECLEA

Techniques and technologies for protection against jamming and cyber-attacks against electronic surveillance systems

ABSTRACT

Scientific Leader

Prof.dr.ing.ec. Mircea BOȘCOIANU

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1 INTRODUCTION

1.1 Justification of the way of framing the theme in the current context

In the current geopolitical context, marked by ongoing military conflicts and the acceleration of technological advancement, electronic warfare (ER) is an essential component of modern military operations. Electronic surveillance (ES), a key element of the wider ER field, was a topic of particular interest to me, on the one hand because of my own experience gained in the operational environment and on the other hand because of the crucial role and influence that the SE has on the success of electronic warfare actions.

In the process of writing the doctoral thesis, essential elements of the activity of electronic warfare specialists, common problems in the management of ES systems and possible solutions identified by applying innovative models and methods of electronic defense of ES systems are integrated into a unitary concept.

1.2 Delimitation of the theme and areas of the research project

Electronic warfare actions are divided into three distinct categories: electronic attack (jamming of various types), electronic defense and SE.

The major components of electronic warfare are Electronic Support Measures (ESMs), Electronic Counter Measures (ECMs) and Electronic Counter-Counter Measures (ECCMs). All three components require support from electronic surveillance.

1.3 Necessity, importance, and timeliness of the theme

A first area (niche) in which no research has been carried out in the field of SE systems is the analysis of the operational environment, i.e. the problems and limitations faced by electronic warfare specialists and operators serving these critical systems.

On the other hand, based on the critical analysis of the current state of knowledge in the field, it was highlighted that the role of electronic warfare is becoming crucial, especially for military aviation, requiring the extensive use of high-tech surveillance and electronic attack systems, advanced electronic countermeasures and modern means such as manned or unmanned research and combat aircraft. Real-time information about the adversary, especially in terms of aviation and air defense, is essential for the success of military operations.

The novelty of the research topic is illustrated by the identification of innovative models and methods of electronic defense of modern electronic warfare systems, models taken from other fields of activity, but which could be adapted to the specifics of the field: the aeronautical safety model, the Monte Carlo method, the Markov chain method, the detection method and the method of estimating the probability of strike.

Another novelty is the application of game theory in the management of SE systems through dynamic allocations (instead of static scenarios) of electronic jamming resources on several enemy air targets acting simultaneously during the air raid.

Another personal contribution explores cognitive electronic warfare and the influence of artificial intelligence (AI) in decision-making processes, addressing the challenges of using AI for situational awareness and decision-making in electronic attack actions, as well as the requirements of the cognitive RE system user and the design of RE cognitive systems.

1.4 Justification for the choice of the thesis title and formulation of the proposed research objectives

The choice of the thesis title is justified starting from personal experience in the field of electronic warfare in general and more directed in the management of SE systems.

Modern jamming protection techniques and technologies are key elements for the success of military operations involving the use of the electronic warfare component. In this context, ES systems play a central role. On the one hand, the results of electronic surveillance provide pertinent early warning indications of risks and threats to one's own forces. On the other hand, SE systems contribute to ensuring the electronic protection of their equipment and systems and support the decision-making process regarding the adversary's combat targets. Effective management of these systems ensures the success of the military operation or can greatly limit the losses recorded in the event of a defeat.

The proposed scientific objectives are the following:

OS1. Identification of the current state of knowledge regarding the management of SE systems in the operational environment;

OS2. Critical analysis of the current state of research in the field of SE systems management ;

OS3. Developing innovative models and methods of electronic defense of modern ER systems;

OS4. Analysis of the possibility of integrating cognitive electronic warfare capabilities into the architecture of current ES systems;

OS5. Analysis of the performance of the most important algorithms for estimating the radio direction (Direction of Arrival - DoA) for combating UAV/UCAV;

OS6. Identification and analysis of cognitive blockages (biases) encountered in ES system operators;

SO7. Analysis of the level of digital skills in military higher education and the perception of the first employers in the operational environment towards young graduates.

The dissemination objective is:

DO Development and implementation of the plan for dissemination and capitalization of the results obtained from the research.

1.5 Research methodology and thesis architecture development

In carrying out the work, conventional techniques and methods specific to the chosen field were used, as well as innovative models, to make up for the lack of data or elements at the confluence between technology and human resources. The proposed studies present scientific relevance through a detailed approach to concepts specific to the field of electronic warfare, such as: analysis of the performance of AoA algorithms used in Counter-UAV systems, the effects of exposure to electromagnetic fields in the context of 6G and IoT technological progress as well as the results of post-COVID digitalization in military higher education.

A novelty element of the research topic consists in the identification of innovative models and methods of electronic defense of modern electronic warfare systems. Regarding human resources, a series of cognitive blockages encountered in the management of ES systems were analyzed, the causes that generate these undesirable situations were described and, finally, possible solutions for each bias were presented.

In order to carry out the research topic study, the "PRISMA 2020" methodology was applied, widely used to carry out a systematic analysis of the literature based on the preferred reporting elements for systematic reviews and meta-analyses.

The information obtained from the case studies, the analysis of the questionnaires and the study of the literature was presented in an accessible and clear way. These results can be a starting point for future research, as the proposed methods are scalable. Specialized literature, transparent information from open sources and fundamental interests and needs in the operational environment were analyzed in depth and formed the basis of personal studies and contributions.

The dissemination of the research results is reflected by the publication of eight BDI articles and two ISI Proceedings articles at the international conference "EDULEARN 2024", on the topic of the research field.

2 RESEARCH ON THE OPERATIONAL ENVIRONMENT AND THE CURRENT STATE OF KNOWLEDGE IN THE FIELD STUDIED

2.1 Evolution of electronic warfare systems management

Electronic warfare is defined as a military action that involves the use of electromagnetic energy for the purpose of determining, exploring, reducing or preventing the hostile use of the electromagnetic spectrum, as well as the action that favors its use for one's own purposes.

Next, the main lessons learned and elements of interest specific to the RE field identified during recent military conflicts were presented, grouped as follows:

- The use of RE in the Korean conflict;
- The use of RE in the Vietnam War;
- The use of RE in the war in the Near East;
- The use of RE in the 1973 Near East War;
- The use of RE in the Arab-Israeli conflict in Lebanon;
- The use of RE in the 1982 Falkland Islands conflict;
- The use of RE in the US-Libya conflict;
- The use of RE in the Gulf War;
- The use of RE in the events of December 1989 in Romania;
- The use of RE in the events of the former Yugoslavia (90s);
- The use of RE in the war in Ukraine.

2.2 Managing electronic warfare assets and highlighting the role of dynamic capabilities

There are a number of theories applicable in resource management, both through a static approach and through a dynamic one.

Resource Based Theory (RBT) is a strategic approach in organizational management that emphasizes the importance of an organization's internal resources in gaining and maintaining a long-term competitive advantage. According to this theory, an organization's strategic resources, which are scarce, difficult to copy, and replace, can be the primary source of competitive advantage.

The basic principle of resource-based theory is that "the whole is more valuable than the sum of the components." This means that an organization's ability to integrate and manage its resources in a synergistic and efficient way can lead to the creation of a total value that exceeds the sum of the value of individual resources.

Transaction Costs Economics (TCE)

TCE is a paradigm in economics that was originally developed by Ronald Harry Coase and later expanded by Oliver E. Williamson. This theory focuses on the analysis of the costs involved in conducting economic transactions between individuals and organizations and how these costs influence the structure and behavior of markets and organizations.

Transactional cost theory (TCE) and SE systems management can be compared as follows:

- Cost and uncertainty management: In the management of ES systems, cost management is also addressed, including the costs of implementation, maintenance and modernization of ER systems. It also addresses the uncertainty associated with the use of technology and data in the current context;
- Limited rationality and asset specificity: in the management of ES systems, limited rationality can be observed in decision-making related to the design and deployment of systems and equipment and asset specificity can be associated with dependence on specialized technologies or resources necessary for the use of these capabilities;
- Governance structure and choice between markets and organizations: in the management of ES systems, this can translate into decisions related to the implementation of new ES techniques and technologies, as well as the choice between outsourcing certain services and maintaining them within the current framework.

Principal Agent Theory (TAP), developed by Michael Jensen and William H. Meckling in their 1976 paper titled "Theory of the Firm: Managerial Behavior, Agency Costs and Ownership Structure," explores the relationship between a company's owners (shareholders or principal owners) and managers hired to run their business. The theory emphasizes that in many situations, the interests of owners and managers can be divergent, as the latter act as agents of the owners and have their own interests and goals.

Similar to the relationship between owners and managers in TAP, in the management of SE systems there are often divergences of interests between the different parties involved. For example, operators may have certain security policy needs and expectations, while system administrators or technicians may pursue different goals, such as operational efficiency or safety.

Creative destruction is an economic concept introduced by the economist Joseph Schumpeter in his work "Capitalism, Socialism and Democracy" (1942). This concept refers to the process by which technological and economic innovations lead to the elimination or replacement of old products, processes or industries with new and more efficient ones.

Just as creative destruction is characterized by innovation and radical change in the economy, the management of ES systems also involves the continuous adoption and implementation of new technologies and techniques to respond to emerging threats and improve the effectiveness of system operation.

Dynamic capabilities are a concept developed by David J. Teece, Gary Pisano, and Amy Shuen in 2009, which refers to an organization's ability to constantly adapt and develop its resources, processes, and competencies to gain and maintain a competitive advantage in an environment characterized by rapid and uncertain technological change.

The use of dynamic capabilities in the field of ER refers to the ability to manage the resources available efficiently and flexibly in ER actions, as well as the ability to adapt and change tactics and technologies quickly according to the evolution of the current situation.

2.3 Case study: questionnaire applied to specialized personnel in the operational environment.

The objective of the questionnaire on 'Current jamming protection techniques and technologies used by ES systems' was to identify ways to identify, classify and protect against jamming of ES systems from the perspective of the factors directly or indirectly involved in this field.

The results of the questionnaire are as follows:

- approximately 97% of respondents answered that they had not participated in such a project that would deal with the issue addressed by this work;
- the distribution on the first position corresponded largely to the need for hiring specialized personnel in a proportion of about 40%, to a lesser extent (24%), about 26% being of the opinion that this classification was carried out defectively;
- In terms of the ability to identify the presence of radio jamming in ES systems, only 28% of those surveyed believe that they can do so and 17% of staff identify the presence of jamming to a lesser extent. This result indicates that only a fraction of the questionnaire participants actually work in this specialized field and not all of them have faced such situations so far;
- about 76% consider themselves specialists in the field of RE (123 out of 247 respondents – largely and 66 out of 247 – to some extent);
- in relation to the implementation of ML (Machine Learning) and AI in ES systems, 49.8% believe that this is largely possible and only 15.38% reject this possibility;
- most respondents, with 78 responses, agree that the human factor could be replaced in the operation of ES systems. 103 people are of the opinion that this is only possible to a certain extent, indicating some limitations or reservations. In addition, 42 respondents believe that the human factor cannot be replaced at all;
- When assessing the opportunity to implement innovative technologies, only 31.58% of respondents believe that AR technology can contribute to the training of ES system operators, 17% of them totally rejecting this possibility.

2.4 Critical analysis of the current state of scientific research in the field of electronic warfare

In the general landscape of current military and security concerns, the research of IS systems occupies a central and strategic position. This importance derives from several factors:

- Rapid technological evolution;

- Complexity of modern threats: threats to national and international security are becoming increasingly diverse and sophisticated, including in the field of ER;
- Integration into electronic warfare;
- Protection of critical infrastructures;
- The link with innovations in the civilian environment.

In the planning phase of the research phase of ES systems, the following aspects are essential:

- Goal setting;
- Analysis of requirements and challenges;
- Alignment with strategy;
- Resource allocation;
- Establishing the deadlines for the execution of the research;
- Assessment of risks and ethical aspects.

Next, a set of specific research questions in the field of electronic warfare was identified:

- What are the latest approaches in the management of ES systems and the relationship between ECM and ECCM?
- What gaps exist in the current research of ES systems?
- How can electronic signal detection and analysis capabilities be improved to counter the adversary's deception and electronic jamming actions?
- What are emerging technologies or innovative concepts that could revolutionize the field of electronic warfare and how can they be effectively integrated into existing military capabilities?
- How can ES systems be optimized and synchronized to ensure complete and efficient coverage of the electromagnetic spectrum in a complex theater of operations?
- What are the current vulnerabilities of ES systems and how can security measures be improved to protect these systems against cyberattacks and sabotage?
- How can advanced data processing technologies be developed and implemented to extract useful and relevant information from the large volumes of data generated by ES systems?
- What are the effective strategies, techniques, tactics and procedures for the use of IS systems in support of military operations, including for the identification and neutralization of threats in real time?
- What are the emerging trends and future directions in the research and development of ES systems in the context of technological evolution and changes in the global security environment?

To answer the study questions posed, a widely used methodology was applied to conduct a systematic review of the literature based on the preferred reporting elements for systematic reviews and meta-analyses (PRISMA 2020). A search of scientific databases comprising important journals and conferences in the field studied such as IEEE Xplore, the ACM digital library, ScienceDirect, SAGE Journals Online and Springer Link was carried out to discover relevant articles in the field of EW.

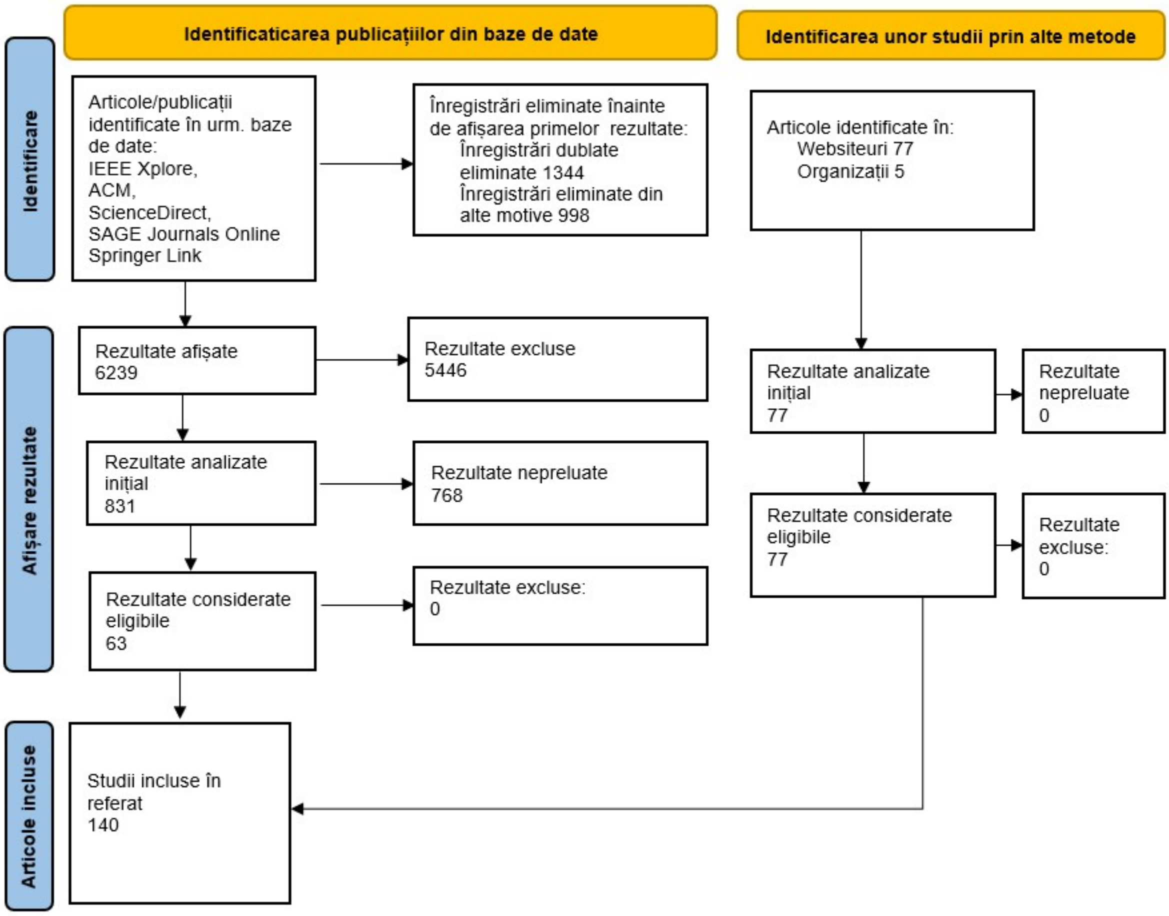

Figure 1: Search diagram by PRISMA 2020 methodology.

Based on the analysis of the collected data and the experience gained in carrying out electronic warfare actions in military conflicts, the following conclusions can be drawn:

- the role of electronic warfare has become increasingly important, for all categories of armed forces, but especially for the air forces;
- increasingly state-of-the-art ES and electronic attack systems, electronic countermeasures (thermal traps and electromagnetic dipoles), unmanned aerial research and combat aircraft, as well as single-use active jamming transmitters, self-guided missiles on the electromagnetic beam of the adversary's electronic means are used;
- support with real-time adversary information (especially aviation and air defense) has a primary role in achieving success in operations;
- While the placement of noise jamming emitters on board combat aircraft proved ineffective, the use of STEALTH technology decisively contributed to the success of the operation.

2.5 Analysis and discussion. Contributions

For the development of electronic warfare means, the following directions of development of the research topic have emerged:

- improving the capabilities of offensive unmanned aerial vehicles and remote electronic research;
- ensuring remote discovery by radiolocation using aerostats and airships, as well as by using dispersed radiolocation stations and systems;
- making the self-steering heads of the missiles in order to be able to distinguish the real target, which usually moves in a horizontal direction, from the trap created with a cloud of dipole reflectors that is stationary or moving vertically;
- the realization of complex means of protection against missiles with radiolocation, infrared and laser self-guidance heads, equipped with automatic systems for quick switching from one protection variant to another;
- achieving electromagnetic compatibility of land, air and sea radiolocation systems.

We also see the integration of AI into ECM systems and the adaptation of electronic warfare payloads to be used on unmanned combat aerial vehicles.

2.6 Partial conclusions

Following the analysis of the local conflicts in which ER was used, carried out after the Second World War, the following conclusions were drawn:

- it has decisively increased the role of electronic warfare in close connection with masking and disinformation in the combat actions of all categories of armed forces;
- it has gone from the separate use of research and jamming equipment during the execution of limited missions to the massive use by aviation, navy and ground troops of research and electronic jamming complexes and destruction by fire of electronic means;
- thermal and radiolocation false targets, offensive, research and electronic jamming unmanned aircraft, single-use active jamming transmitters and self-guided missiles on the electromagnetic beam of electronic means of destruction are increasingly widely used;
- it is necessary to have information about aviation and the adversary's air defense in real time; the best methods of real-time data acquisition have proven to be the airborne service of research aircraft and the use of artificial satellites of the Earth;
- the automated systems of control of electronic warfare means have been diversified, the harmonious combination of the possibilities of electronic research and electronic jamming in a continuous process has been imposed as a requirement;
- The installation of a noise jammer on an aerial platform did not lead to its concealment, but, on the contrary, to its unmasking.

3 ARCHITECTURE OF ELECTRONIC WARFARE SYSTEMS and METHODS/MODELS USED IN THEIR MANAGEMENT

3.1 Current geopolitical and technological context, strategic objectives and description of the new paradigm

The negative impact of the continuation of the war in Ukraine is being felt in the economy and supply chains are still facing bottlenecks. The term "greedflation" describes an inflation driven by greed, given the unjustified increase in prices and record rates of corporate profits over the past 10 years. Rising interest rates can induce an economic recession. Labor productivity is declining, while the unemployment rate is increasing. In Europe, the absence of recession is due to demand exceeding supply by 2-3%, and consumer appetite is declining.

Digitalization in the military environment has become a concept of our days again, especially after the outbreak of war by the Russian Federation in Ukraine and implies, on the one hand, a collective technological progress and, on the other hand, a process of transformation.

According to Eurostat data, as of 2021, in terms of basic or higher digital skills, the Netherlands (Netherlands until 2020) ranks best with a percentage of almost 80%. Of the states considered to have strong armies, France has 62%, Italy 46%, and Turkey only 30%. Romania ranks last, after Bulgaria (31%), with only 28% of the country's population having basic or higher digital skills.

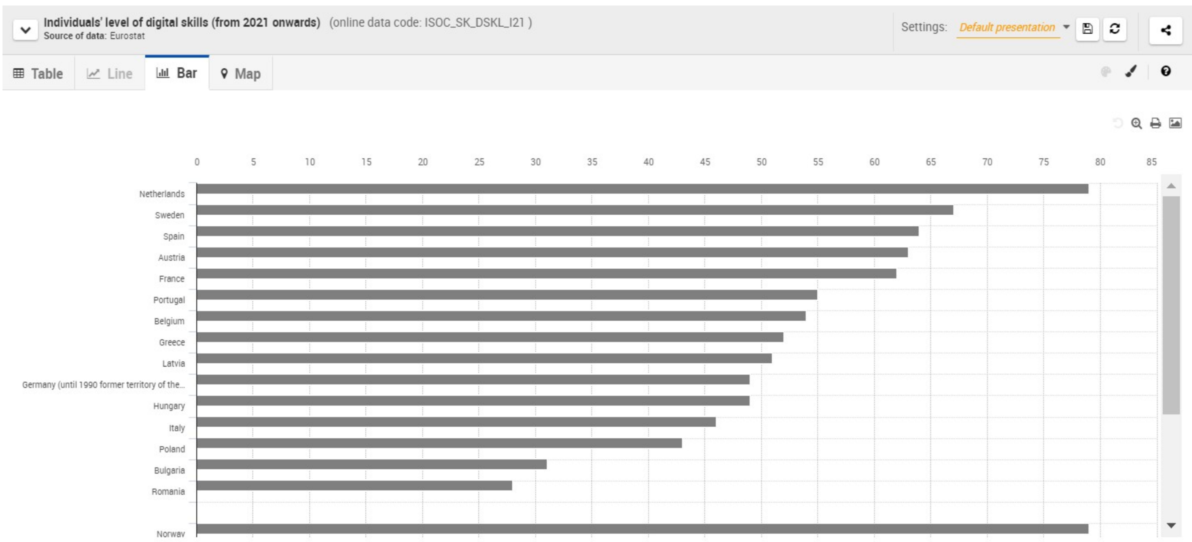

Figure 2: Percentage of the population with basic digital skills in EU/non-EU Member States

The percentages are somewhat similar when we talk about the level of digitization at which the armies of the European Union member states are located.

The new current concepts more common in the civilian environment, such as AI, IoT, blockchain, Big Data, ML, AR, virtual reality, extended reality, mixed reality, quantum computing, will have to be included in the existing military ones (e.g. C4I2SR).

3.2 Scalability and modularity of sub-systems in electronic surveillance architectures

Scalability refers to the ability to expand or reduce the system according to the requirements and resources available, while modularity refers to the ability to break down the system into independent and interconnectable components, which facilitates its adaptation, maintenance and modernization.

- Scalability: Allows the system to scale up or down in size or capacity to meet varying environmental and user requirements. For example, an SE system can be scalable to handle a larger number of sensors or integrate new technologies such as ML or AI;
- Modularity: allows the system to be divided into independent modules or sub-systems, each responsible for a specific functionality or component of the system.

By implementing scalability and modularity in the architectures of ES systems, their adaptability, flexibility and ease of maintenance are ensured, allowing them to respond efficiently and effectively to changes in their operating environment and new user requirements.

3.3 Managerial aspects regarding the integration, installation, evolution and decommissioning of electronic surveillance systems

The integration of a fully functional system involves bringing together the various components: hardware, software, communications and the human factor, each having responsibilities at all levels, from management and decision-making to execution (operation and maintenance). To ensure effective integration, an incremental approach is essential, allowing for the gradual integration of sub-systems. In this process, problems with the interface between sub-systems often arise, and one of the causes may be the uncoordinated supply of system components.

The installation process, carried out by the supplier, must ensure that the installed product meets the customer's needs (in our case, the SE system managed by the beneficiary). However, the premises assumed by the supplier regarding the customer's needs may be incorrect, which can lead to unsatisfactory results. It is also necessary to take into account the human resistance to change, which can be manifested by the personnel involved in the management of the new equipment. During the transition period to the new system, it is possible that it will work in parallel with the old installed system, and its installation may encounter problems related to wiring or physical installation. In order to ensure an effective implementation and operation of the new system, it is essential that the human resource participates in training activities and qualification courses.

The period of evolution of an ES system extends from the moment of commissioning to the decommissioning of the system (by scrapping). Although large systems are expensive and have long lifespans, they need to evolve to meet changing demands.

The process of decommissioning/scrapping the system takes place at the end of its life, with the decision to decommission it. In this process, the aim is to efficiently recover subsystem components, which can be used as spare parts for other systems, and to recycle materials. At the same time, it is necessary to responsibly manage hazardous materials and take appropriate protective measures to prevent environmental pollution.

3.4 Analysis of OPS (Organizations-People-System) relationships, human factors and organizational processes typical of electronic warfare systems. Situations of cognitive blocks

The connection between the intelligence process (the production of information) and the implications of electronic warfare in this process will be detailed throughout this section. There are no analytical tools for analyzing a large volume of information in the field of electronic warfare and it is necessary to process a lot of information/electromagnetic signals in a very short period of time.

The empirical evaluation of the impact of electronic warfare on the battlefield in the success of a military operation can be compensated by the design and implementation of "Electronic Warfare Intelligent Information System" (EWIIS) systems (automatic processing, communications and non-communications, radiolocation data, electronic maps, command-control and combat mission planning).

Electronic warfare and obtaining information from all sources are of fundamental importance for carrying out information operations. Based on information in particular from the field of SIGINT (Signal Intelligence – information obtained on the basis of signal analysis), EOB can be generated, an electronic attack mission (jamming) can be successfully planned and executed and protection against similar actions by the adversary can be ensured.

Bias is a cognitive block that generates errors specific to summary processing of crisis situations or conflict situations. The causes come from the limits of human memory or from certain influences in the social environment. In the management of ES systems, the following biases are identified:

1. Information bias is the tendency to collect as much information as possible, even if obtaining it cannot ultimately affect the quality of the decision made.

2. The bias of exaggerated confidence in one's own abilities (false superiority)

False superiority is manifested by the tendency of operators, usually those with more experience, involved in the management of SE systems to minimize their own negative characteristics and to overestimate their qualities and achievements, especially compared to others.

3. Confirmation bias is the tendency to favor information that confirms their beliefs or assumptions already present and to reject information that contradicts those prejudices or to give them much less importance.

4. Attention illusion bias is the illusion of thinking that we are noticing everything that is happening around us. In fact, we only notice certain elements on which we are focused. It occurs especially in the situation that involves solving new tasks. As we become more experienced, problems are solved more easily, without high consumption of mental energy.

5. *Availability bias* refers to the tendency of operators of electronic warfare systems to consider that certain situations, things occur more frequently if they can be found in their memory. Conversely, if certain situations have not corresponded in the past, they are considered unlikely or have not occurred.

6. *Control bias* refers to the tendency of operators to erroneously overestimate their ability to control situations or the outcomes of events.

7. Attribution bias manifests itself in the situation where the success obtained is justified by internal factors (one's own merit) and the failures are justified by external or situational factors.

8. Risk compensation bias – The Peltzman effect, represents the tendency of individuals to adapt their behavior according to the level of risk perceived at a given time. We behave more cautiously when we perceive a higher risk and less cautiously when the risk is reduced.

9. Choice support bias is a cognitive block that retroactively attributes positive characteristics to a decision made in the past and negative characteristics to options that were not taken into account, and is caused by the fact that the decision-making process was preceded by analysis and planning.

10. Monte Carlo bias represents the tendency to consider that if an event happens more frequently in the present, it will happen less often in the future and vice versa, if certain situations are rarer now, the frequency of their occurrence in the future will increase. The blockage is based on the belief that there is a universal law of balance, which is counterproductive and dangerous in certain situations.

10. Monte Carlo bias represents the tendency to consider that if an event happens more frequently in the present, it will happen less often in the future and vice versa, if certain situations are rarer now, the frequency of their occurrence in the future will increase.

11. The survivor's bias consists in considering only the happy situations, which were successful even though they were risky, and rejecting those with an unhappy ending. The chances of success based on previous favorable experiences are overestimated, and the events that led to failure are not considered.

12. Anchoring bias is the tendency to turn to a source of information to answer a certain question. The blockage is highlighted when a certain opinion is expressed "by guessing", without a viable argument.

13. The unrealistic optimism bias occurs when we have the impression that we are less exposed to risk compared to those around us. The blockage can be accompanied by false superiority over the group of those around them, considered "average". The opposite bias of unrealistic optimism is that of unrealistic pessimism.

14. The normality bias represents the belief that things, the environment, future events will not go out of normality, will not have a dramatic evolution. The blockage is based on underestimating the possibility of a disaster as well as the effects of that critical situation.
15. Lazy bias occurs in certain individuals who, being within a group, tend to make less effort to achieve the group's objectives, compared to the effort made to achieve individual objectives, outside the group.
16. The bias of social comparison appears in situations of rejection of those around us for the simple reason that they seem superior to us (physically, intellectually or mentally). The blockage of social comparison is closely linked to social status.
17. Authority bias involves the tendency to blindly trust information coming from a certain person or superior authority.

3.5 Emerging electronic defense techniques and technologies used in the management of modern electronic warfare systems.

Jamming techniques in the field of communications are classified as follows:

- noise jamming;
- pulse jamming;
- cheating jamming (spoofing);
- sliding jamming;
- Eye jamming;
- jamming;
- tracking jamming;
- adaptive jamming;
- intelligent jamming.

According to the Joint Allied Doctrine for Cyberspace Operations, "the Alliance operates in increasingly interconnected environments, in particular cyberspace and the information environment (IE)".

Innovative models and methods of electronic defense of modern electronic warfare systems in the context of Industry 4.0

1. The SMS-ICAO (Safety Management System - International Civil Aviation Organization) safety management system model includes organizational structures, responsibilities, policies and procedures, and can be applied and adapted in the management of electronic warfare systems. An ICAO SMS - SMRE correspondence is illustrated in the figure below:

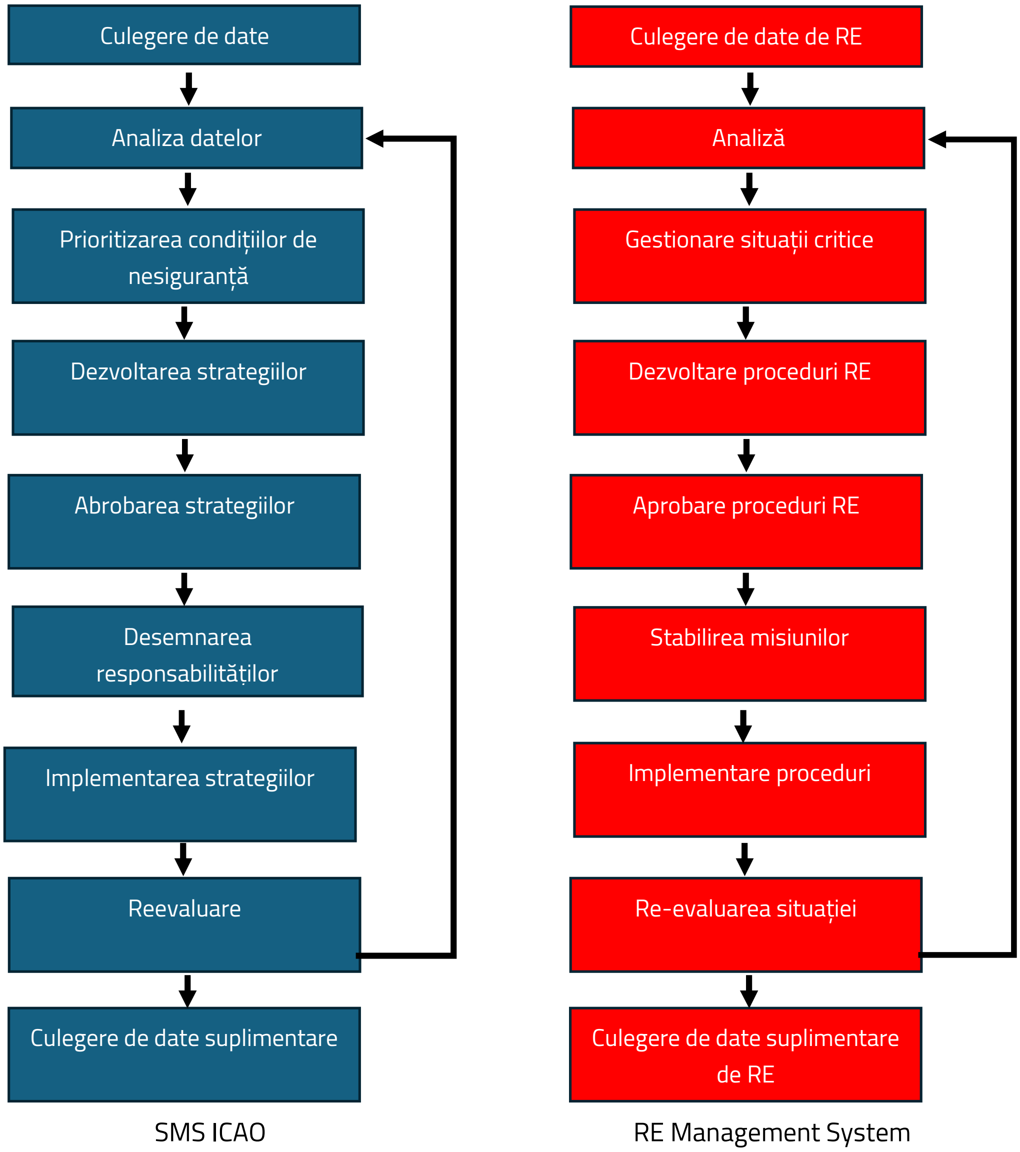

Figure 3: SMS ICAO – EW system management

The electronic warfare management system is built with the fulfillment of some essential conditions:

- through a corporate approach;
- implementation of effective organizational tools;
- feedback mechanisms for improving the activity.

Parallel SMS-QMS (Quality Management System) -SMRE:

The Quality Management System (QMS) has two component parts:

- quality control;
- quality assurance;

The State Safety Program (SSP) has four components:

- establishing state security policies and objectives;
- state security management;
- ensuring state security;
- promoting state security.

The SMS-QMS-EMRE common parts are as follows:

- the activities are planned and managed judiciously;
- success always depends on the outcome of the analyses and monitoring work;
- for an efficient functioning, all functions, processes and human factors in the organization/structure are involved;
- The actions/activities carried out can be and are permanently improved.

2. Monte Carlo method

In the case of this method, the operation of a system is simulated using statistical methods with the help of random processes. The areas in which the Monte Carlo method can be used are:

- operational research: study of service systems, stock management, PERT method (Program Evaluation and Review Technique);
- numerical calculus: solving multiple integrals, solving differential equations; Dirichlet problem;
- economics: the study of materials management, management games, the development of a branch, areas, economies, the distribution and production process;
- industry: work processes, optimal distribution of machinery, transport problems;
- other fields: biology, chemistry, fluid mechanics, nuclear physics, natural phenomena, etc.

The Monte Carlo method can be applied as follows:

- Simulation of the technical capabilities of electronic warfare systems;
- Evaluation of the effectiveness of electronic warfare techniques, tactics and procedures;
- Analysis of risks and vulnerabilities;
- Optimization of resources and strategies;
- Anticipating technological progress.

3. The Markov chain method is a technique used in the field of electronic warfare for modeling and analyzing the behavior of electronic defense systems in the context of a series of possible events or states. This method is based on the concept of stochastic processes, where system states are determined by random events and dependent on the previous state of the system. The application of the Markov chain method in the context of electronic defense of modern electronic warfare systems involves:

- Modelling of system states: a number of states of the electronic defense system are identified and defined, such as alert status, threat detection status, reaction status and others;
- Definition of transitions between states: the probabilities of transition between the different states of the system are established;
- Simulation of the evolution of the system;

- Performance analysis and optimization: based on the results of the simulations, the performance of the electronic defense system can be evaluated and possible improvements and optimizations can be identified;
- Anticipating and adapting to change.

3.6 Integration of game theory into the management of electronic surveillance systems

The application of game theory in the management of IS systems can be essential for understanding and adequately addressing the interactions between different entities involved in this field. This need stems from the complexity of strategic relationships and decisions within SE systems.

Identify and highlight the possibility of integrating game theory aspects into the management of ES systems.

The application of game theory in the management of IS systems can support:

- Strategy optimization: game theory provides analytical tools and frameworks for analyzing and developing optimal strategies in the context of complex interactions between actors involved in electronic surveillance;
- Conflict management: as the interests of different entities can be divergent or even conflicting within ES systems, game theory can provide frameworks for managing and resolving these conflicts;
- Analysis of interdependencies: game theory can help to understand and analyze the interdependencies between the decisions made by the different entities involved in the management of ES systems;
- Risk Anticipation and Management: By using game theory, risks associated with decisions and actions within SE systems can be identified and assessed.

3.7 Analysis and discussion. Personal contributions

The chapter focused on mapping the architecture of the ES systems, the scalability and modularity of the sub-systems as well as the integration, installation, evolution and decommissioning of the ES systems. Subsequently, a series of frequently encountered biases in the management of the ES systems and the ways out of these bottlenecks were identified.

A personal contribution has been made in identifying innovative models and methods of electronic defense of modern electronic warfare systems, including how to integrate game theory into this architecture. The importance of integrating risk and resilience management elements into ES systems was also highlighted in order to ensure their efficient and secure operation in the face of current threats and risks.

3.8 Partial conclusions

In this chapter dedicated to the architecture of electronic warfare systems and their management methods, the topics addressed included: the current geopolitical and technological context, together with the new paradigms, scalability and modularity of sub-systems in ES architectures and the integration, installation, evolution and decommissioning of ES systems. Finally, the topic of risk management and resilience in ES systems was addressed.

4 PERFORMANCE MANAGEMENT OF ELECTRONIC SURVEILLANCE SYSTEMS

4.1 Objectives and description of the performance issues of electronic surveillance systems

In this chapter, the objectives to be achieved regarding the performance management of ES systems will be identified:

- Identification of strategies to manage the vulnerability of ES systems;
- Highlighting the emergent properties specific to these systems;
- Listing some elements of reliability engineering with applicability in the management of ES systems;
- Analysis of ESG-AI and ESG-AHP-AI parallels in SE systems management;
- Highlighting the influence of AI in decision-making processes specific to the ER field.

4.2 Strategies for managing the vulnerability of electronic warfare systems

Managing vulnerabilities in electronic warfare systems is essential to ensure the security and effectiveness of these systems in the face of increasingly diverse and sophisticated threats. Important strategies for managing these vulnerabilities include:

- Assessment and identification of vulnerabilities;
- Implementation of security measures;
- Continuous monitoring of SE systems;
- Training staff to be able to recognize and manage vulnerabilities;
- Continuous security updates and continuous improvements of protection systems.

By implementing these strategies and approaches, RE structures can manage the vulnerabilities they face and ensure the security and reliability of their systems and equipment.

Next, the limits of the High Reliability Organization (HRO) theory and the Natural Accident Theory (NAT), applied in the field of SE systems management, were identified.

4.3 Emergent properties specific to electronic surveillance systems

These emergent properties can be divided into two categories: functional and non-functional:

- Functional emergent properties occur when all elements of the system work together to achieve a specific goal;
- On the other hand, non-functional emergent properties (such as reliability, performance, safety, and security) are associated with the behavior and performance of the system in its operational context.

4.4 Emerging issues in the management of electronic surveillance systems. The role of ESG (Environmental, Social, and Governance) and AI (Artificial Intelligence)

ESG and AI are two distinct areas, but they may have some overlap or interactions in the context of certain aspects. ESG refers to the non-financial criteria used by investors and other stakeholders to assess the performance of a company or organization in terms of its impact on the environment, society and corporate governance practices. This concept focuses on issues such as carbon reduction, social responsibility, diversity and inclusion, transparency and business ethics.

Integrating ESG and AI concepts into the management of ES systems can bring multiple benefits and contribute to improving the performance and sustainability of these critical systems. In this context, these concepts can be applied as follows:

Environmental:

- Using AI technologies to optimize the energy consumption of ES systems;
- Implementation of emissions and ecosystem impact monitoring solutions in the areas where these military systems are deployed;

Social Aspects:

- The integration of AI into IS systems can help increase security and performance by quickly detecting and preventing incidents and special activities in the field of electronic warfare;
- Ensuring diversity and inclusion in the teams that develop and manage these systems, to promote different perspectives and create more equitable and socially responsible technologies.

Governance:

- Implementation of policies and procedures for the management of data and information in accordance with regulations and standards regarding their protection and confidentiality;
- Using AI for data analysis and generating reports and analyses on the performance and impact of SE systems in different areas, including ESG issues.

4.5 Cognitive electronic warfare – the influence of AI in decision-making processes specific to electronic surveillance

The AI techniques used in the field of RE refer to:

- electronic situational awareness (EOB), in the field of ES (signal characteristics, classification, anomaly detection, recognition of future intentions, causal reasoning);
- decision-making, in the areas of electronic protection, electronic attack and RE planning (planning, optimization, material and time resource management);
- ML – learning or enhancing performance based on processed data, both for situational awareness and in the decision-making process.

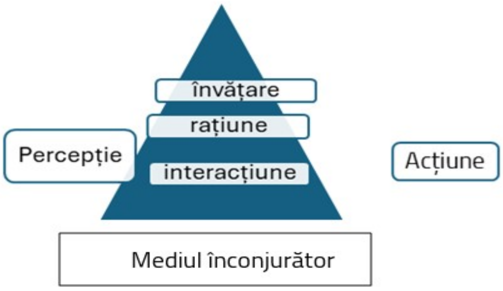

Figure 4: Structure of a cognitive system

A cognitive system perceives the environment, analyzes the situation and acts in order to achieve the goal, learning from the interaction with that environment. The transformation of a classic electronic warfare system into a cognitive system is carried out based on the performance of the three basic functions with the help of AI.

The cognitive cycle is similar to the decision-making cycle, used in the military environment: Observation-Orientation-Decision-Action (OODA – Observe, Orient, Decide and Act). The main difference lies in the fact that the OODA cycle refers to a process, while the cognitive process to the human factor takes place based on that decision-making process.

Table 1: AI - Electronic Warfare Actions

AI Terminologies	Classic EW Terminology
Situational awareness	Electronic support
Decision	Electronic protection and electronic attack
Execution monitoring	Assessment of losses incurred in the scope of RE
Learning	Rescheduling of RE actions (data and software updates)

Challenges of using AI for situational awareness

The challenges of using AI for Situation Awareness (SA) in Electronic Support (ES) actions and measures and in the Electronic Warfare Battle Damage Assessment (EW) process are as follows:

- The cognitive EW system is extremely dynamic: the results of situational awareness are valid for a very short time and can change even before a decision is made;
- Ambiguity of input data: certain events on the EW line can have multiple causes and generate diverse and even erroneous conclusions;
- The partially unknown nature of the factors influencing EMS (Electromagnetic Spectrum) which may generate an erroneous assessment of losses incurred in the field of EW (EW BDA);
- Complex interactions between the control parameters of a cognitive EW system are not always "correctly understood" and can negatively influence the performance of the system as a whole;

- Feedback loops within the cognitive EW system are very complex and run over different periods of time (longer or shorter), which can negatively influence the cause-effect correlations of the actions taken;
- In an increasingly complex electromagnetic environment, it is very difficult to generate enough data and scenarios for the "training" of the cognitive EW system.

Analysis of the interdependencies between cognitive radio networks and cognitive ER systems

The main link is represented by the fulfillment by cognitive radio networks of the electronic protection objectives of cognitive EW systems. On the other hand, the benefits of effective management of the electromagnetic spectrum obtained in cognitive communication networks will also have to be "transferred" to cognitive EW systems.

Conception and design of cognitive RE systems

The following aspects will be taken into account in the design activities of cognitive ER systems:

- decision-making mode: centralized or decentralized;
- learning process: setting learning tasks and monitoring this process;
- detection system: level of sensitivity required, elimination of redundant data, types of radio frequency detention of signals;
- security policies: data encryption, restricted access to the network, protection of AI models used in the cognitive system that could be compromised and later copied by reverse engineering;
- software architecture: the aim is to optimize both the cognitive EW system and the component subsystems in general;
- Hardware component: refers to the design of equipment with certain capacities for storing, archiving and processing data and information.

For the design of a cognitive EW system, it will be analyzed how AI can or cannot replace the human factor in the following components:

- knowledge of the situation in EMS (electromagnetic environment) for SE;
- making the decision for a specific ER action: electronic attack or electronic protection;
- continuous learning and improvement, through ML tools.

For efficiency, it is recommended to gradually introduce artificial intelligence in a regular EW system by subsystems and tasks, until it is transformed into a fully cognitive one.

Learning methods can be divided into two distinct categories:

- methods based on learning from previous experiences: new situations interfere with those stored in the database without prior planning of a training period;
- Model-based methods: Data obtained from previous learning experiences generate a model with certain parameters. The number of parameters (model size) and the period of interference of new situations with the created model remain constant. The

periods of time allocated to learning are directly proportional to the volume of data required during this process.

Multi-source data fusion

For an optimal knowledge of the situation in the electromagnetic environment, the operators of the ES systems, but especially the analysts and decision-makers, will interpret data collected from multiple sources: radar systems, airborne, terrestrial or maritime unmanned systems, ships, space systems, aircraft, antennas and various sensor networks. The fusion of this wealth of data and information falls under the responsibility of an EW cognitive system.

A multi-source data fusion model is shown in Figure 13. It starts from the evaluation of the initial data and the objects (data sources) that contribute to the knowledge of the current situation.

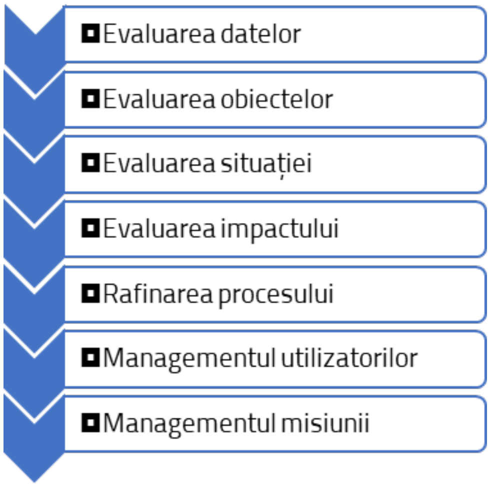

Figure 5: Multi-source data fusion model applicable to a cognitive EW system

An example of how ML technology can assist the fusion of multi-source data ("multi-intelligence" – multi-INT) is localization with the help of the 5G standard, used in mobile telephony, and the concept of "contextual knowledge". With the help of 5G technology, mobile equipment could become "aware" of their location and make "assumptions" about the state of affairs of the user of that mobile equipment. Table 7 shows the key performance indicators that contribute to the localization of 5G equipment.

Table 2: Key performance indicators that contribute to the localization of a 5G equipment.

Key performance indicators	Description
Position location accuracy	The difference between the estimated position of the located equipment and its actual position
Speed accuracy	The difference between the estimated speed of the localized equipment and its actual speed
Orientation accuracy	The difference between the estimated orientation of the located equipment (usually from the North direction) and its actual orientation

Latency (delay)	The time it takes to determine and display the position of a 5G device
Refresh rate (update)	Localized equipment position refresh rate
Energy consumption	The energy required to determine the position of a 5 G equipment
System scalability	The number of devices that can be located in a given unit of time, with a certain "update" rate.

Electronic protection and electronic attack

Even if in the classical sense of defining the concepts of electronic warfare, the two components (EP and EA) are defined and analyzed separately, by introducing AI in the composition of EW systems, they use common algorithms and constructive solutions. The only difference lies in the way the objectives are defined: in the case of electronic protection, the objectives refer to one's own, friendly forces, and electronic attack actions always target the adversary.

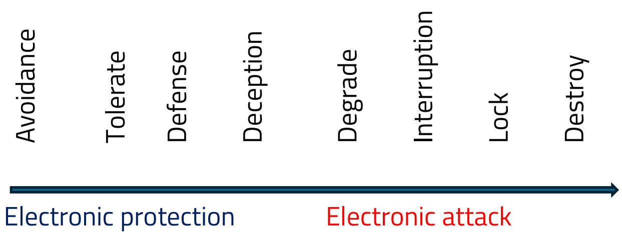

Figure 6: Spectrum of protection and electronic attack actions.

Decision theory in the case of a complete cognitive EW system is based on three distinct concepts:

- Planning of electronic warfare actions according to the set objective;
- Optimizing or selecting an optimal course;
- Applying the optimal decision/course;

In the classic planning process of electronic warfare actions, we encounter:

- preparation of the concept of the operation - CONOPS (concept of operations), of the operation plan, OPLAN (operation plan) and of the courses of action - CA (at least two);
- selecting a CA;
- application of the Operation Order, OPORD (Operation Order), based on the accepted CA.

Table 3: Planning of RE actions

Cognitive EW System	Classic EW system
Action planning	CONPOPS, OPLAN and courses of action
Optimizing actions	CA selection
Implementation of the decision	OPORD

Substantiating decisions in conditions of excessive volatility and uncertainty

In a complex and increasingly crowded electromagnetic environment, very rarely is the information fully known. The decision-making algorithms will include and argue the uncertainty factor of current information. With the support of active detection measures and deliberative communications, the quality and certainty of information is increased, and a series of theories are applied in this process:

- the DEMPSTER-SHAFER theory, which measures the degree of confidence of the information (hypotheses) by probabilistic calculation of the evidence that supports those hypotheses;
- the theory of unclear logic: by which the truth value of some initial data is analyzed;
- argumentation theory: through which reasoned determinative relationships are built between evidence (initial data) and conclusions, eliminating conflicting or opposing information.

Designing a human-machine interface within a cognitive electronic warfare system

An efficient human-machine interface will be intuitive, flexible, extensible and will respond in a timely manner to the requests of the operators of the cognitive EW system, fulfilling the following objectives:

- increasing operational performance;
- increasing operating efficiency;
- management of excess tasks and missions assigned to combat systems operators (EW systems, air, land or naval platforms) and operations planners.

The design of an efficient human-machine system is especially critical for good situational awareness in the electromagnetic environment (SA – Situation Assessment). Its operation is illustrated in Figure 15. The human-machine system transforms the actions of the human operator into commands for electronic equipment, and the data generated by the sensors of these equipment will be analyzed and interpreted by the human factor.

These transformations are static and do not change depending on the operator, the technical system used or the operating environment. The intervention of AI through the concept of "human-machine teaming" (HMT – Human-Machine Teaming) to a cognitive system, through ML algorithms makes these transformations dynamic. It is intended that the actions of the human operator and the processes automated through ML become complementary, permanently observing the following principles:

- responsibility towards the human factor;
- knowledge of speculative risks and benefits;
- maintaining respect and security in operation;
- maintaining honesty in the proper functioning of technical systems.

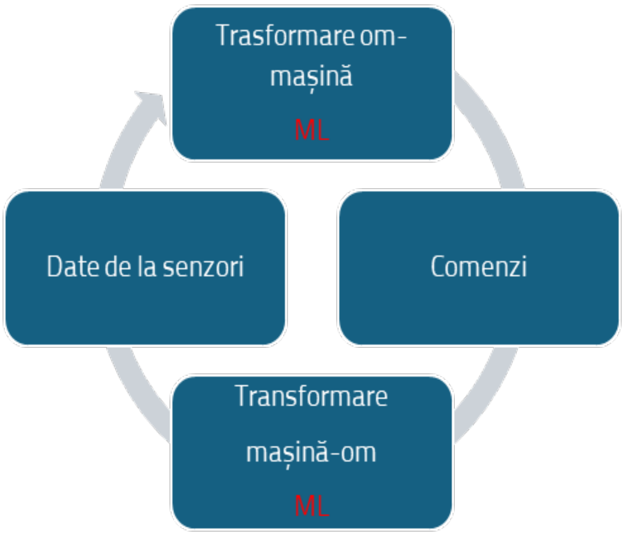

Figure 7: Operation of a human-machine system

Methods of activating learning processes in the field of electronic warfare

In order to increase the quality of decisions and the entire process of planning combat missions, in the architecture of cognitive EW systems there are several ways of activating learning (RL - Reinforcement learning), as follows:

- the neural network model, (ANN - Artificial Neural Networks);
- the model of support vector machines (SVM – Support Vector Machines);
- the MAB (Multiarmed Bandit) approach;
- the Markov Decision Trees (MDP) method, for processes under uncertainty;
- by the method of "Deep-Q" networks (Deep Q-Networks - DQNs).

4.6 Personal contributions

In the context of ES systems performance management, during Chapter 4, a series of strategies for managing the vulnerability of ES systems were identified, the emerging properties specific to these systems were highlighted, some reliability engineering elements with applicability in the management of ES systems were presented and the parallels of ESG-AI and ESG-AHP-AI in the management of ES systems were analyzed.

An important contribution aimed to study cognitive electronic warfare and the influence of AI in decision-making processes, addressing the challenges of using this technology for situational awareness and decision-making in electronic attack actions. The requirements of the user of the cognitive ER system and the ways of designing cognitive systems were presented. Issues related to electronic support, electronic protection, electronic attack, management of ER actions, decision-making under uncertainty and the application of game theory in a cognitive ER system were also analyzed, as well as the development of the human-machine interface and the application of machine learning (ML) methods.

4.7 Partial conclusions

In this chapter, the objectives and strategies for managing the vulnerability of electronic warfare systems and their specific emergent properties have been explored. Also, the reliability engineering elements applicable in the management of SE systems, the integration of ESG and AI principles in this field, as well as the influence of AI in decision-making processes, within the concept of cognitive ER, were analyzed.

5 CASE STUDIES CARRIED OUT DURING THE RESEARCH

5.1. Analysis of the performance of AoA algorithms used in Counter-UAV systems

The case study presents a synthesis and analysis of the performance of the most important algorithms for estimating the direction of arrival (DoA). DoA estimation is defined as the process of determining the angle of radio incidence in relation to a series of antennas whose elements are well synchronized and located.

The effectiveness of countermeasure systems is largely based on the performance of the implemented estimation algorithm. This study addresses the performance of four such algorithms (MUSIC, Root-MUSIC, ESPRIT and CAPON). These algorithms were analyzed based on variations in spectrum errors.

The reasons why AoA algorithms are necessary for counter-UAV systems are:

- Detection;
- Pursuit;
- Classification;
- Localization;
- Neutralization.

AoA algorithms for counter-UAV solutions

Finding the most suitable Angle of Arrival (AoA) algorithm for use in counter-UAV systems is a critical element of system design. The choice of the AoA algorithm can significantly influence the detection, location, tracking, and neutralization capabilities of the system.

A. MUSIC (Classification of multiple signals)

This algorithm uses the proper structure of the covariance matrix of the received signal to estimate the AoA. MUSIC provides high-resolution AoA estimates, but it requires a high computational cost and the number of sources to be less than the number of array sensors.

If we assume N is the number of network sensors receiving D signals, then we can represent this as:

$$X=A(S)+N \qquad (1)$$

Here, X is the sensor outputs, A is the direction matrix, S is the signals, and N is the noise.

The spectrum of MUSIC is defined as:

$$\boldsymbol{P_{MUSIC}(\theta)} = \frac{\mathbf{1}}{\boldsymbol{abs}\,[\boldsymbol{a^H(\theta)E_N E_N^H a(\theta)}]} \qquad (2)$$

Where a(θ) is the direction vector, EN is the eigenvector matrix of noise vectors, and H is the Hermitian transposition.

B. Root-MUSIC

This is a variant of the MUSIC algorithm with a lower computational intensity. Root-MUSIC finds the roots of a polynomial and selects the roots corresponding to the directions of the signal. Like the MUSIC algorithm, it also requires the number of sources to be less than the number of matrix sensors.

Instead of finding vertices in the MUSIC spectrum, it solves a problem with polynomial roots. This algorithm is more computationally efficient.

The roots of the polynomial are given as:

$$\boldsymbol{P(z) = a^H(\theta)E_N E_N^H a(\theta) = 0} \quad (3)$$

The angles of arrival are estimated from the roots located on the unit circle.

C. ESPRIT - estimation of signal parameters by rotational invariance techniques

This algorithm uses the own structure of the received signal, but has lower computational requirements than MUSIC because it does not involve a search over the entire angle space. However, it requires a specific matrix structure (e.g., a uniform linear matrix with distance at half wavelength).

Let S1 and S2 be two signal arrays separated by a known distance. We can express the two matrices as:

$$\boldsymbol{S1 = A(\theta)D + N1} \quad (4)$$

$$\boldsymbol{S2 = A(\theta)e^{-jkd}D + N2} \quad (5)$$

This algorithm estimates the angle in the subspace of the signal directly using the rotational invariance property.

D. Capon/MVDR - Minimal Variance Distorted Response

MVDR forms a narrow beam in the direction of the desired signal and nulls in the direction of interference, which can be beneficial for environments with interference signals. However, it requires an accurate estimation of the covariance matrix, which can be difficult in non-stationary environments.

It has lower computational requirements than MUSIC and ESPRIT, but requires an accurate estimate of the covariance matrix.

The weight vector w that reaches MVDR is:

$$\boldsymbol{W_{capon} = \frac{R_{xx}^{-1}A(\theta)}{A^H(\theta)R_{xx}^{-1}A(\theta)}} \quad (6)$$

And the Capon spectrum is given by:

$$\boldsymbol{P_{capon} = \frac{1}{A^H(\theta)R_{xx}^{-1}A(\theta)}} \quad (7)$$

The choice between these algorithms or others depends on the specific requirements and constraints of the counter-UAV system. The performance of these algorithms can also be improved by using them in combination or by optimizing their parameters based on the operating environment.

Determination of AoA in MATLAB simulations

In this MATLAB scenario, an array of antennas was simulated to analyze the performance of different AoA estimation algorithms (MUSIC, Root-MUSIC, ESPRIT, and MVDR/Capon). The simulation will allow to understand how the number of sensors in an antenna array affects the spectrum error of each algorithm.

To carry out this study, a synthetic scenario was created in which signals are received from multiple sources (emulating UAVs) at different known angles. An array of antennas was used to receive these signals, and the AoA was estimated using each of the algorithms considered.

After establishing the estimated AoA, one can calculate the spectrum error by comparing the estimated spectrum and the actual spectrum. The actual spectrum can be obtained based on the known AoAs of the sources, while the estimated spectrum can be obtained from the AoA estimation algorithms.

The stages of the scenario are as follows:

- Installation: The scenario involved an antenna array with a variable number of sensors (2, 4, 6, 8). There were two sources (UAV simulation) placed at -20 degrees and 30 degrees, respectively. The signal-to-noise ratio (SNR) for the received signals has been fixed at 10 dB;
- Signal generation: For each sensor configuration, signals are generated from the two sources, adding Gaussian noise to the signal from each sensor to ensure an SNR of 10 dB;
- AoA estimation: Using the signals received at the matrix, the AoA estimates are calculated, using each of the four algorithms;
- Spectrum Error Calculation: Once the estimated AoA angles are known, the estimated spectrum will be calculated based on these AoA. As the true AoA of the sources are known (-20 degrees and 30 degrees), one can calculate the real spectrum. The spectrum error can then be calculated as the difference between the estimated spectrum and the actual spectrum for each algorithm;
- Analysis of the results: the steps for each sensor configuration were repeated and how the spectrum error varies depending on the number of sensors in the array for each algorithm was analyzed.

Measurement results and analysis

MUSIC provides high-resolution AoA estimates and is effective when the number of sources is less than the number of antennas. However, it requires high computing power, which may not be feasible for real-time applications. This limitation may be more pronounced with larger antenna arrays (e.g., 8 antennas). For arrays with only 2 antennas, MUSIC may not be the best choice if there are more than two sources.

Root-MUSIC requires less computational power than MUSIC. It is also necessary that the number of sources is less than the number of antennas, so it may not be suitable for the array with only 2 antennas if there are more than 2 sources. For larger antenna arrays (4, 6 or 8 antennas), Root-MUSIC can be a good choice if high-resolution estimates are required and computational resources are not a major constraint.

ESPRIT also provides high-resolution estimates and requires less computing power than the MUSIC algorithm. However, it requires a specific array geometry (such as a uniform linear array with half-wavelength spacing) and may not be suitable for arrays with fewer antennas (such as 2). With 4, 6 or 8 antennas, ESPRIT can be a good choice, provided that the requirement of matrix geometry is met.

MVDR/Capon: These methods form a narrow beam in the direction of the desired signal. Although they can be effective with a small number of antennas, they require an accurate estimation of the covariance matrix, which can be difficult in rapidly changing or non-stationary environments. These methods could provide a good balance between performance and computational complexity for antenna arrays of sizes 2 to 8.

In conclusion, since the flight of a UAV is very fast and unpredictable, the algorithm to be used must be very fast in calculation and accurate. For small to moderate array applications (2 to 8 antennas) where high resolution is required and computational resources are not a constraint, methods such as MUSIC, Root-MUSIC, or ESPRIT might be more suitable.

However, methods like MVDR and Capon could offer a good compromise between complexity and performance. The final choice depends on specific requirements, such as the desired trade-offs between accuracy, computational complexity, and robustness, as well as the characteristics of the signals and the environment in which the algorithm will be implemented.

5.2. Exposure to electromagnetic fields in the context of 6G and IoT technological progress

In the present case study, the influence of electromagnetic waves on certain tissues in the human body was analyzed. For the analysis of electromagnetic fields, the simulation software "ANSYS" was used, developed by ANSYS Inc., an important leader in the fields of engineering and simulation.

Through the modules dedicated to electromagnetic fields: ANSYS HFSS (High-Frequency Structural Simulator) and ANSYS Maxwell, the program allows engineers and researchers to model and simulate the behavior of electromagnetic fields in a wide range of scenarios.

The three frequencies chosen (2 GHz, 5 GHz and 8 GHz) are relevant in the study of the interaction between electromagnetic waves and human tissues for several reasons. The first reason is common use in wireless communications: 2 GHz, 5 GHz, and 8 GHz frequencies are frequently used in wireless communication applications such as Wi-Fi networks, mobile phone networks, and other wireless devices.

For the three tissues, the following simulation cases were established:

Table 4: Cases of simulation of the interaction of electromagnetic waves with human tissues

Tissue	Parameters	Radiation source
Tissue 1	2 GHz	2 GHz
	5 GHz	5 GHz

	8 GHz	8 GHz
Tissue 2	2 GHz	2 GHz
	5 GHz	5 GHz
	8 GHz	8 GHz
Tissue 3	2 GHz	2 GHz
	5 GHz	5 GHz
	8 GHz	8 GHz

The waveguide has been designed with the following dimensions:

a) 1510 x 300 x 300 mm for the 2 GHz simulation;

b) 610 x 120 x 120 mm for the 5 GHz simulation;

c) 385 x 80 x 80 mm for 8 GHz simulation.

The waveguide lengths have been selected to provide far-field conditions at the end of the waveguide (length > 10 λ, condition fulfilled for the selected frequencies: 2 GHz, 5 GHz and 8 GHz). This object has been referred to as a "waveguide". Inside the waveguide, a surface with a thickness of 3 mm was inserted. This surface, i.e. the object, was called a "sample". Reference cases at 2, 5 and 8 GHz are considered to be those where the sample has air parameters. A diagram of the geometric structures of the waveguide and the sample is shown in Figure 16.

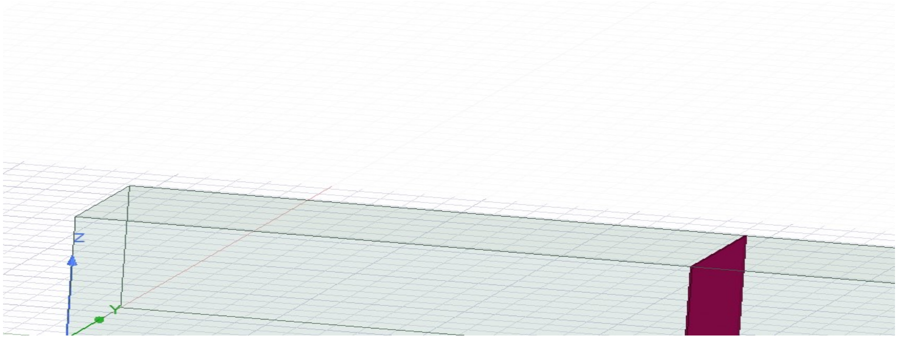

Figure 8: Diagram of the geometric structures of the waveguide

The sample is placed at a distance of 1000 mm from the input port and 507 mm from the output/measurement port, for case 1 (2 GHz).

In order to have the most accurate results and to make an analysis as precise as possible, the table below has been completed with the conductivity and permeability parameters of the three chosen tissues:

Table 5: Permittivity and relative conductivity of three types of tissues at certain frequencies

Tissue	Parameter	f = 2 GHz	f = 5 GHz	f = 8 GHz
1. Leather (dry)	εr	38.6	35.8	33.2
	σ [S/m]	1.27	3.06	5.82
2. Blood	εr	59.0	54.0	48.6
	σ [S/m]	2.19	5.4	9.87

3. Brain (Cerebellum)	εr	45.7	41.1	37.1
	σ [S/m]	1.82	4.19	7.42

It is observed that the electrical permittivity decreases with increasing frequency, while conductivity increases with increasing frequency. Therefore, at all selected frequencies, the highest permittivity and electrical conductivity is that of the blood. For simulation purposes, it will be assumed that all tissues have a relative magnetic permeability μr=1, although blood contains iron. The iron content of the blood is also reflected in the main parameters mentioned in Table 13. The parameters presented above were used to simulate the propagation of electromagnetic fields through the selected tissue types.

It is hypothesized that human tissues have an impact on the propagation of electromagnetic waves. To assess this impact, a waveguide shall be considered. At one end, it is considered a source of electromagnetic waves, and at the other end, the strength of the electric field has been measured by means of a surface. For reference, the waveguide is filled with air. A surface with a thickness of 3 mm has been inserted between the source and the observation surface, and the attenuation introduced by it will be evaluated later. The evaluation can be carried out in several ways, but as a comparison criterion, the maximum intensity of the electric field (E [V/m]) will be chosen.

The waveguide version described above will only allow the comparison of results between different tissues at the same frequency, while the comparison between frequencies will only be made with the values related to the air sample. The electromagnetic wave source has a power of 1 watt (default in HFSS). The type of solution selected was modal, single-mode. After running the simulation, the electric field strength through the output port was generated in a 2D plane, and the maximum value was retained for each simulation case. In Figure 18, the strength of the electric field through the output port is represented. The maximum field strength for case 1 (the sample is air, at the frequency of 2 GHz) is 140.551 A/m (present at a phase angle of about 90°). This is not the only angle at which the maximum amplitude is reached, but only one of the representations selected for the characterization of the field strength. The introduction of various materials as a sample instead of air has an impact on both the maximum strength of the field and the phase at which it occurs. In order to determine the phase at which the high field strength is present at the measurement port, the occurrence of the maximum field strength was investigated using the FIELD OVERLAYS/ANIMATE function. The "animation" was made between 0° and 359° with 36 steps because this has a slight impact on the accuracy of the maximum calculated amplitude.

Discussions and interpretation of results:

At all selected frequencies, blood was the sample that had the greatest attenuation of electric field strength. Since the measurement plane was located at least 10 wavelengths from the source, it can be considered a far-field measurement, and the magnetic field is coupled with the electric field. Therefore, this result is true for electromagnetic waves. Brain tissue attenuated electromagnetic fields more than skin tissue at all frequencies. The mitigating factors were significant.

5.3. Aspects regarding the post-covid digitalization of military higher education

The case study presents the introduction of augmented reality (AR) in the management of military higher education at the university level. This was one of the objectives and results of the project entitled Implementing digitalization in defense higher education (DDHE). The initiative was carried out as a collaborative initiative known as the "Partnerships for Digital Education Readiness" project, involving four military universities in Europe.

The following research questions were asked:

- Will the introduction of AR in educational management have measurable positive results?
- Are teachers receptive to adopting new instructional approaches, especially those that facilitate practical applications that link theoretical concepts with real-world contexts?
- Can the use of AR be extended to all subjects taught?

In order to carry out this research, questionnaires were administered annually to the students of the "Henri Coanda" Air Force Academy in Brașov between 2019 and 2023, covering the pandemic and the post-COVID-19 period. The aim was to assess students' perspectives on their digital competences, access to available digital resources and the evolution of their interest in the subjects in which the AR educational tools have been integrated.

An additional set of questionnaires was applied annually, covering the same time frame, to the initial employers of the Academy's graduates. They aimed to assess employers' satisfaction levels with graduates' digital skills, the extent of their practical training and the perceived degree of creativity and adaptability of young officers to new techniques and technologies.

The student satisfaction questionnaire was developed on two dimensions: satisfaction and importance. It contained 30 items grouped into two categories: access to educational resources and digital skills. To assess students' overall satisfaction with these dimensions, the questionnaire also included a recommendations and suggestions section.

The items were evaluated on a LIKERT scale with 5 points, both in terms of satisfaction and in terms of the importance of each aspect for the student, where 1 means not at all satisfactory/unimportant, and 5 means very satisfactory/very important.

The questionnaire addressed to employers was developed on a single dimension – satisfaction and contained 30 items grouped into two categories: practical skills and creativity/adaptability and included at the end, a section of recommendations and suggestions.

The results showed significant improvements in the subjects in which AR educational methods were used. Students showed more interest in the subjects in which AR technology was introduced (mixed reality glasses "Microsoft HoloLens 2" and specific applications). The average of the results obtained by the students in the analyzed group increased from 7.25 in the academic year 2019-2020 (without the introduction of AR resources) to 7.35 in the academic year 2020-2021, the maximum reached being 7.56, in the period 2022-2023. The pass rate increased during the analyzed period: in the academic year 2019-2020, there were 8 arrears, their number decreasing to 2, in the period 2022-2023.

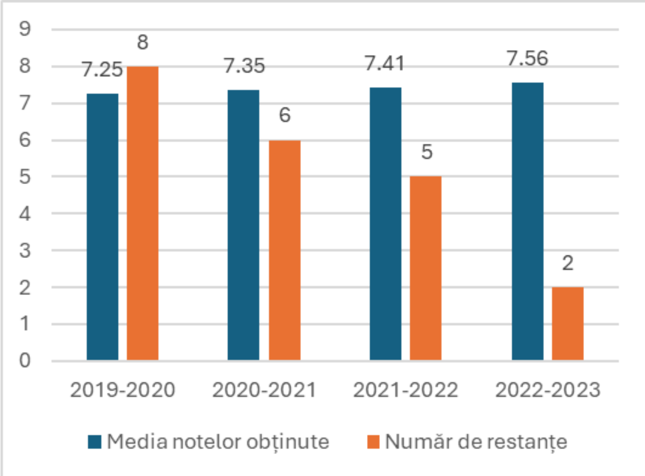

Figure 9: Results of the introduction of AR in the educational process

Bachelor's theses, especially those with a practical component, which included AR, obtained better grades compared to works without AR elements.

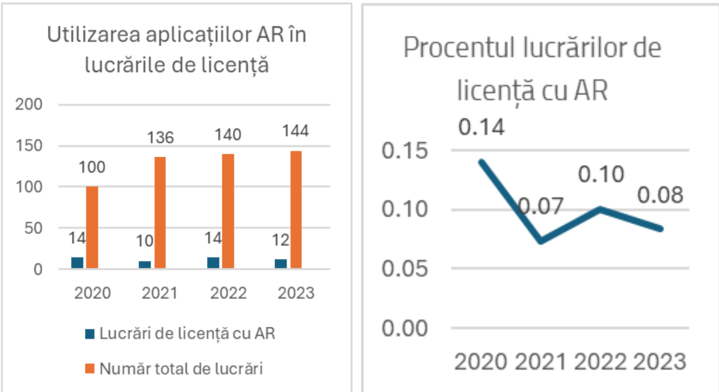

Figure 10: Using AR Applications in Bachelor's Degree Papers

As shown in Figure 20, interest in the new technology was higher in the first year of implementation (2020), with 14 bachelor's papers out of a total of 100 (14%) using AR applications, with maximum grades obtained. In the following years, interest in AR technologies decreased even more, with the percentage of work with AR applications being between 7% and 10%.

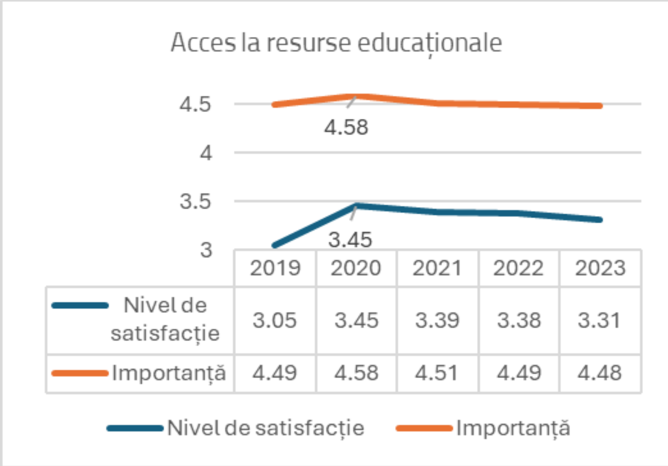

Figure 11: Access to educational resources.

The students noted the improvement of digital skills and easier access to resources with the implementation of AR. Their perception of access to educational resources peaked in 2020, with the introduction of new technologies and remained at high levels in the following periods. The scores obtained, 4.58 at the level of satisfaction and 3.45 at the level of importance, out of a maximum of 5, fully confirm this.

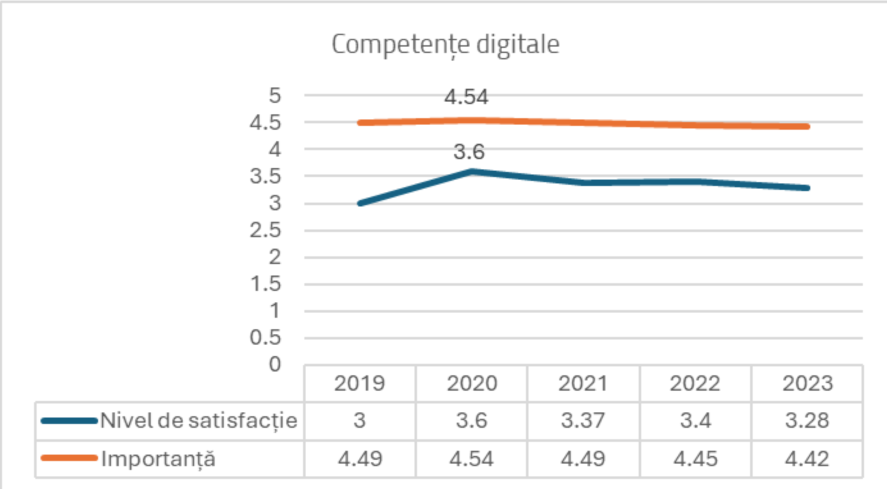

Figure 12: Perception of acquired digital skills.

On the other hand, the perception of acquired digital skills was at its highest level in 2020, with similar scores: 4.54 at the level of satisfaction and 3.6 at the level of importance, out of a maximum of 5. Employers also appreciated graduates improved practical skills and digital skills due to AR integration, noting the increased creativity and adaptability among young officers.

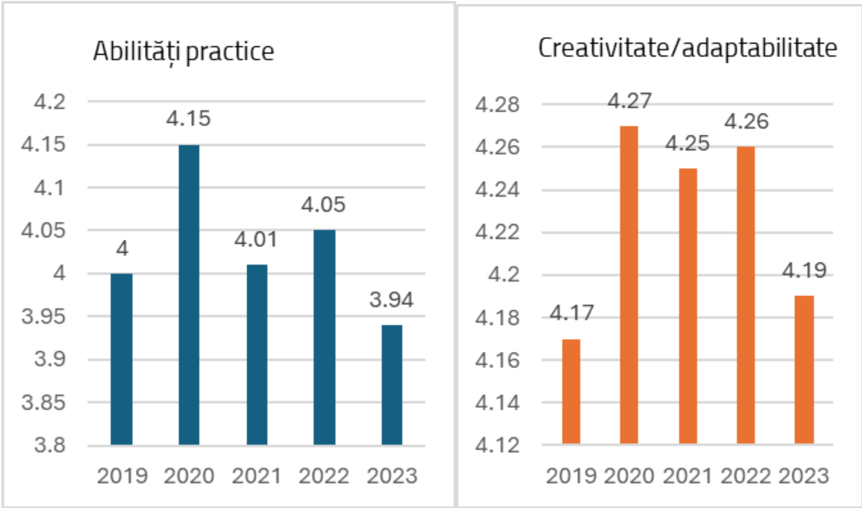

Figure 13: Employers' perception of digital skills, creativity and adaptability to new technologies

Employers' perception of digital skills and graduates' creativity and adaptability to new techniques and technologies peaked in 2020, with the introduction of new technologies, and remained at high levels in the following periods. The scores obtained: 4.15 at the level of digital skills of new employees and 4.27 at the level of creativity and adaptability to new techniques and technologies, out of a maximum of 5, confirm this.

In conclusion, it can be considered that the introduction of AR resources in the educational process has brought measurable benefits to both teachers and students and graduates of the educational institution. The process of digitization of military higher education is ongoing, and quantifiable results are still being identified.

6 CONCLUSIONS, CONTRIBUTIONS, FUTURE DIRECTIONS, MANAGERIAL IMPLICATIONS

6.1 Conclusions

Electronic warfare involves the use of electromagnetic energy in military actions, with the aim of detecting, analyzing, restricting or preventing the hostile use of the electromagnetic spectrum, but also facilitating its use for one's own benefit.

Electronic surveillance, an essential component of electronic warfare, involves actions taken to investigate and intercept the electromagnetic signals emitted by the adversary, in order to locate and recognize them quickly, in order to identify threats and effectively use this information for the benefit of their own forces.

In the doctoral thesis entitled **"Techniques and technologies for protection against jamming and cyber-attacks in the management of electronic surveillance systems",** the knowledge and experience gained in the operational environment were applied and a series of possible original contributions in the field of electronic surveillance systems management were identified.

In the current context, marked by the current border war, the importance of electronic warfare has become crucial. Urgent modernizations, reorganizations and adaptations are needed in the field to the new conditions. The rapid progress of technology and changes in the geopolitical environment have radically changed the typology of new threat scenarios to national security and security. The information obtained with the help of modern IS systems can be a strategic advantage for one's own forces and the lack of it leads to a certain failure in a current armed conflict.

In the introduction of the thesis, included in the first chapter, the way of approaching the subject in the contemporary context was argued, the thematic limits and the areas covered by the research project were established, the relevance and topicality of the subject were highlighted, and the current scientific context was presented. Finally, the research methodology and the structure of the architecture of the thesis as a whole were established.

In chapter 2, entitled "Research on the operational environment and the current state of knowledge in the field studied", the evolution of the management of electronic warfare systems was investigated, the operational environment was analyzed through a questionnaire addressed to specialized personnel and the current state of knowledge in the field was performed. Electronic warfare resource management and dynamic capabilities were also analyzed. The brainstorming process was used to generate innovative ideas and solutions, and open-source data was analyzed to complement and validate the information obtained. In the discussions on the design of use, planning and research of electronic surveillance systems, various strategies and approaches were explored and finally a critical analysis of the current state of research was carried out to identify gaps and opportunities for development.

In chapter 3, dedicated to the architecture of electronic warfare systems and their management methods, the topics addressed included: the current geopolitical and technological context, together with the new paradigms, the scalability and modularity of sub-systems in electronic surveillance architectures and the integration, installation, evolution and decommissioning of electronic surveillance systems. New emerging electronic defense techniques, technologies, and ways to integrate game theory into the management of electronic surveillance systems were subsequently identified. Finally, the topic of risk management and resilience in SE systems was addressed.

The next chapter entitled "Performance Management of Electronic Surveillance Systems" explores the objectives and description of the problems in this sphere, the strategies for managing the vulnerability of electronic warfare systems and their specific emergent properties. It also analyzes the reliability engineering elements applicable in the management of ES systems, the integration of ESG and AI principles in this field, as well as the influence of AI in decision-making processes, within the concept of cognitive electronic warfare.

In chapter 5, dedicated to case studies, various aspects were investigated, such as the analysis of the performance of AoA algorithms in Counter-UAV systems, exposure to electromagnetic fields in the context of 6G and IoT technological advancement, and the implications of digitalization in military higher education in the post-COVID era.

6.2 Personal contributions

C2.1 The first contribution consists of the results of the questionnaire applied to electronic warfare specialists in the operational environment. These are set out in detail in Section 2.3. About 97% of the respondents have not previously participated in projects similar to the issue addressed in the paper. The distribution on the first position was considered appropriate by about 40% of respondents, while 26% considered that it was not done properly. Only 28% of those surveyed feel able to identify the presence of radio jamming in electronic surveillance systems, and 17% felt they could do so to a lesser extent. Also, about 76% of respondents consider themselves specialists in the field of electronic warfare. There are differences of opinion among respondents regarding the possibility of replacing the human factor in the operations of electronic surveillance systems. The majority, with 78 votes, claim that the human factor could be replaced to some extent, while 103 people indicate reservations or limitations in this regard. In addition, 42 respondents believe that the human factor cannot be replaced at all, reflecting concerns about the ability of technology to make complex decisions and interpret context instead of humans. Regarding the implementation of innovative technologies, only 31.58% of respondents believe that AR technology can contribute to the training of operators of electronic surveillance systems, while 17% completely reject this possibility.

C2.2 The second contribution refers to the results of the critical analysis of the current state of research. For this, the PRISMA 2020 methodology was applied to carry out a systematic review of the literature, using the preferred reporting elements for systematic reviews and meta-analyses. Relevant articles in the field of electronic warfare have been identified in scientific databases such as IEEE Xplore, ACM Digital Library, ScienceDirect, SAGE Journals Online and Springer Link. The conclusions refer to the fact that the role of electronic warfare is becoming decisive, especially for the air force, requiring the extensive use of state-of-the-art surveillance and electronic attack systems, advanced electronic countermeasures and technologies such as unmanned reconnaissance and combat aircraft.

C3.1 The third contribution refers to the identification of innovative techniques, models and methods of electronic defense of modern electronic warfare systems, models taken from other fields of activity but which could be adapted to the specifics of the thesis: the aeronautical safety model, the Monte Carlo method, the Markov chain method, the detection method and the Method of estimating the probability of hitting.

C4.1 The fourth contribution explores cognitive electronic warfare and the influence of artificial intelligence in decision-making processes, addressing the challenges of using AI for situational awareness and decision-making in electronic attack actions, as well as the user requirements of the cognitive EW system and the design of EW cognitive systems.

C.5.1 The case study presenting a synthesis and analysis of the performance of the most important algorithms for estimating the direction of arrival (DoA) is **the fifth** original contribution. DoA estimation is defined as the process of determining the angle of radio incidence in relation to a series of antennas whose elements are well synchronized and located. This study addresses the performance of four such algorithms (MUSIC, Root-MUSIC, ESPRIT and CAPON). These algorithms were analyzed based on variations in spectrum errors. The term "error" refers to the difference or discrepancy between the estimated AoA values obtained from the algorithms and the actual AoA values. In this case, the error represents how accurately the algorithms can determine the actual angles of arrival. The final choice of a radio direction estimation algorithm depends on specific requirements, such as the desired trade-offs between accuracy, computational complexity, and robustness, as well as the characteristics of the signals and the environment in which the algorithm will be implemented.

C.3.2 The sixth contribution refers to human resources. A series of cognitive blockages encountered in the management of electronic surveillance systems were analyzed, the causes that generate these undesirable situations were described and, finally, possible solutions for each bias were presented.

C5.2 The next (seventh) contribution consists of the results of the questionnaire applied to students and first employers in the operational environment.

6.3 Justification of originality

The central element of the thesis consists of the two case studies based on the results of the questionnaire applied to students and first employers in the operational environment and the questionnaire applied to electronic warfare specialists in the operational environment and the third case study that presents a synthesis and analysis of the performance of the most important algorithms for estimating radio direction.

For example, according to the answers received, about 76% consider themselves specialists in the field of electronic warfare (123 out of 247 respondents – to a large extent and 66 out of 247 – to a certain extent), a relatively high percentage.

6.4 Themes and future research directions

A possible future direction of research could consist in the development and periodic application of questionnaires in order to connect military decision-makers to the pragmatic realities in the operational area specific to the field of electronic warfare.

Another future direction of research could be to assess the impact of implementing a machine learning method within a proprietary electronic surveillance system.

In the field of combating UAVs/UCAVs, a new direction of research could involve the identification of new AoA (Angle of Arrival) determination algorithms that eliminate the trade-offs on accuracy, computational complexity and robustness of the systems used.

6.5 Making the most of the research results.

The dissemination of the results has resulted in participation in several international research projects and the publication of several articles at national and international conferences. 8 BDI articles and two ISI Proceedings articles were published at the EDULEARN 2024 conference, on the theme of the research field. These have been extensively detailed in the "LIST OF PUBLISHED WORKS" section.

6.6 Research methodology and thesis architecture development

In conducting the work, conventional techniques and methods specific to the chosen field were used, as well as innovative models, to make up for the lack of data or elements at the confluence between technology and human resources. The proposed studies present scientific relevance through a detailed approach to concepts specific to the field of electronic warfare, such as: analysis of the performance of AoA algorithms used in Counter-UAV systems, the effects of exposure to electromagnetic fields in the context of 6G and IoT technological progress and the results of post-covid digitalization in military higher education.

The novelty of the research topic results from the identification of innovative models and methods of electronic defense of modern electronic warfare systems. As far as human resources are concerned, a series of cognitive blockages encountered in the management of electronic surveillance systems were analyzed, the causes that generate these undesirable situations were described and, finally, possible solutions for each bias were presented.

Treating the objectives in the manner described gives the thesis originality and innovative character, managing to arouse the interest of electronic warfare specialists and researchers in the field.

In order to carry out the research topic study, we applied a widely used methodology to conduct a systematic literature review based on the preferred reporting elements for systematic reviews and meta-analyses (PRISMA, 2020).

The information obtained from the case studies, the analysis of the questionnaires and the study of the literature was presented in an accessible and clear way. These results can be a starting point for future research, as the proposed methods are scalable. Specialized literature, transparent information from open sources and fundamental interests and needs in the operational environment were analyzed in depth and formed the basis of personal studies and contributions.

In the research paper, I capitalized on my practical experience gained in the territory, using engineering and management methods, as well as statistical techniques. The thesis is structured in six chapters and corresponding annexes, meant to provide a more detailed explanation of the ideas presented. The approach used makes the thesis both interdisciplinary and multidisciplinary, with objectives anchored in the specificity of the management of electronic surveillance systems in the Romanian Army's endowment.

Multidisciplinary involvement in scientific projects during the doctoral program

National projects

I am actively involved in the "**PNRR DIGIMIL AFA**" project. Between September 19, 2022 and December 31, 2025, in the "Henri Coanda" Air Force Academy, the 1357725267 Code Project entitled "DIGIMIL AFAHC (Integrated DIGItalization of the MILitary Henri Coandă Air Force Academy) University, in the amount of 12,549,073.00 lei, financed by the Ministry of Education as coordinator of reforms and investments within the call for Grants for the digitization of universities from Component 15 – Education of the National Recovery Plan and Resilience of Romania (PNRR), Reform 5: Adoption of the legislative framework for the digitization of education, Investment 16: Digitization of universities and their preparation for the digital professions of the future. The project was approved by the Order of the Minister of Education no. 4168/30.06.2022 on the approval of the List of universities selected for funding under the call for projects "Grants for the digitization of universities"

Another project I am participating in is entitled "**Mobile Module for Ensuring Energy Autonomy from Sustainable Sources – MMAAESS",** within the PSCD (Sectoral Research and Development Plan) and runs between 2024 and 2026.

They are also part of the team of a project that coordinates, develops and implements UAV/UCAV with special purpose, FLIR sensors and GPS, the beneficiaries being structures from the national defense system.

International projects

Active participation in the Erasmus+ DDHE project (Implementation of Digitalization in Defence Higher Education)

Through the KA2 action of the Erasmus+ program, common study modules have been developed to standardize the curricula in specialized programs in the defense system, including mobilities and traineeships for students and teaching staff. These modules, created before the pandemic, had a complementary role to face-to-face education (F2F). However, careful research has shown that the main disadvantages of these modules lie in the teaching/learning methods that are not adapted to the pandemic context. Thus, the "Henri Coanda" Air Force Academy (AFAHC), together with its partners, proposed a solution to eliminate, at least partially, the classic format of teaching materials.

In order to achieve the project's goal of increasing the level of students' preparation by updating the teaching/learning methods to the current context and following the needs analysis in the partner academies, the following objectives were set:

- Improving the digital skills of teachers in partner universities;
- Increasing the involvement and attractiveness of the research process for students;
- Introduction of digital educational resources;
- Implementation and integration of VR and AR systems in the teaching/learning process in all partner universities;
- Create a database containing all project materials.

During the project, colleagues (professors and students) from European organizations were mainly involved in the dissemination process, at different stages, in order to achieve a high international impact and a high rate of transferability of the project results.

A correct and successful project development includes the design, implementation, evaluation, and dissemination stages. In line with the objectives of the project and considering the categories of target groups, the following activities were planned:

- Creation of digital educational resources for 12 disciplines, both technical and humanities;
- Design and development of VR/AR applications for the selected disciplines, depending on their profile and specificity, being particularly useful for technical disciplines that include practical lessons;
- Introduction of all educational resources in an open-access digital library, available to the universities within the project and their partners, in the future.

Personal contributions to scientific projects

Within the DDHE project, we developed digital content for the "Radar Fundamentals" discipline, including progress assessment and interactive elements created with the "eXe_Learning" software program. These materials consist of 10 courses and 7 applications, which were made available to students from participating institutions.

Within the Grant Scheme "Digitization of universities and their preparation for the digital professions of the future", funded through the National Recovery and Resilience Plan, we designed the architecture of a radiolocation and electronic warfare laboratory, equipped with modern equipment, "Chrome Book" consoles, dedicated RF software and a large interactive display.

Within the project "**Mobile Module for Ensuring Energy Autonomy from Sustainable Sources – MMAAESS",** within the ongoing PSCD (Sectoral Research and Development Plan), I participate in the equipment procurement phase.