



Technological Research and Innovation 2025

**MINISTRY OF DEFENCE
NATIONAL ARMAMENTS DIRECTORATE**



Presentation of the National Armaments Director	Pag.	4
Foreword by the Director III Department	Pag.	6
A look at the Organization	Pag.	9
Research in the national context	Pag.	17
Research in the international context	Pag.	101
Statistical - financial summary	Pag.	115
Abbreviations and acronyms	Pag.	121

PRESENTATION

BY THE NATIONAL ARMAMENTS DIRECTOR

The volume *“Technological Research and Innovation 2025”* gathers and highlights the main outcomes of defence research activities completed in 2024, funded and managed by the National Armaments Directorate. These initiatives were developed within the Directorate’s statutory mandate on defence technological innovation, with the aim of seeking advanced technological solutions, strengthening the operational superiority of national defence capabilities, and preserving national technological sovereignty.

Technological innovation today, more than ever, represents an indispensable element for ensuring the effectiveness and resilience of military capabilities. The rapid evolution of emerging technology domains such as artificial intelligence, quantum technologies, hypersonic systems, space-based capabilities, remote and autonomous systems, biotechnology, and others—just to name a few—generates new operational opportunities but simultaneously imposes crucial challenges: what may offer a decisive competitive advantage to national defence can also turn into a threat if used by hostile or non-state actors. The Russian-Ukrainian conflict has forcefully highlighted how contemporary war theaters have deeply changed: alongside traditional factors of conventional confrontation, dual-use technologies such as drones and commercial satellite communications and digital networks adapted for military purposes are becoming increasingly significant. In this context, responsiveness and the ability to achieve technological overmatch are becoming decisive factors for both national and collective security.

To face these challenges, it is essential to have a solid national industrial and research base. Only through real technological autonomy can Defense ensure continuous access to



and use of systems, platforms, and equipment without external constraints, whether temporal or geographical.

The Italian Defense is strongly committed to promoting and supporting innovation, recognizing the central role of the industrial sector’s excellences, including start-ups, academia, and research centers. In this context, the National Defence Research Plan is the main open innovation tool designed to create virtuous connections between Defense and the national research and innovation ecosystem, fostering synergies, co-developments, and technological cross-pollination.

An additional strategic asset is represented by active participation in international cooperation initiatives, particularly within NATO - through the Science and Technology Organization (STO) and the NATO Defence Innovation Accelerator for the North Atlantic (DIANA) - as well as within the European Defence Agency (EDA).

These multilateral contexts are essential to strengthening the collaborative dimension of research, maintaining a high shared technological level, and enhancing Italy's contribution to the Euro-Atlantic security landscape.

Investing in military research ultimately means investing in the future of the country. The economic, industrial, and social impacts generated by these activities go far beyond the defense

sector, fueling national innovation, fostering high-skilled employment growth, and contributing to building a safer, more resilient, and technologically advanced society.

National Armaments Director
Vice Admiral
Giacinto OTTAVIANI

FOREWORD

BY THE DIRECTOR III DEPARTEMENT – TECHNOLOGICAL INNOVATION

In the field of military planning, time is the most critical resource to manage, as it is the only resource that cannot be regenerated or recovered.

Vehicles, equipment, supplies and even personnel can be replaced — but time cannot, *tempus fugit*, and *la recherche du temps perdu* is merely the subject of a novel, not even science fiction, in which the protagonist must ultimately surrender to the inevitability of the passage of years and the changes that come with it.

We can strive to keep pace with time, but we cannot overcome it. And the real challenge is keeping pace with it, making the best possible use of it to drive process and technology innovation, without ever surrendering to the dynamics of change, which are not always favorable. Instead, we must strive to manage them and even try to anticipate them with our vision. Those who are able to steer and anticipate technological and strategic shifts gain a decisive competitive advantage, which translates

into stability and economic growth in the civilian domain, and into deterrence and threat-response capability in the military domain.

The fundamental enabler in responding effectively to evolving requirements is Defence Research & Innovation, an indispensable prerequisite for innovation. Time can, therefore, become the best ally of our armed forces if we dedicate the necessary attention and appropriate funding to military research, following a cyclical and iterative model that never settles for achieved results but builds upon them to go further. The effects of such investments, in fact, belong to everyone, as they generate positive spill-over effects in the civilian sector.

Research activities, if conducted responsibly and properly, not only enrich the cultural heritage of humanity but also generate concrete benefits for society, which, in any case, translate into an essential factor for progress.

The Director
Dr. Giovanna ROMEO

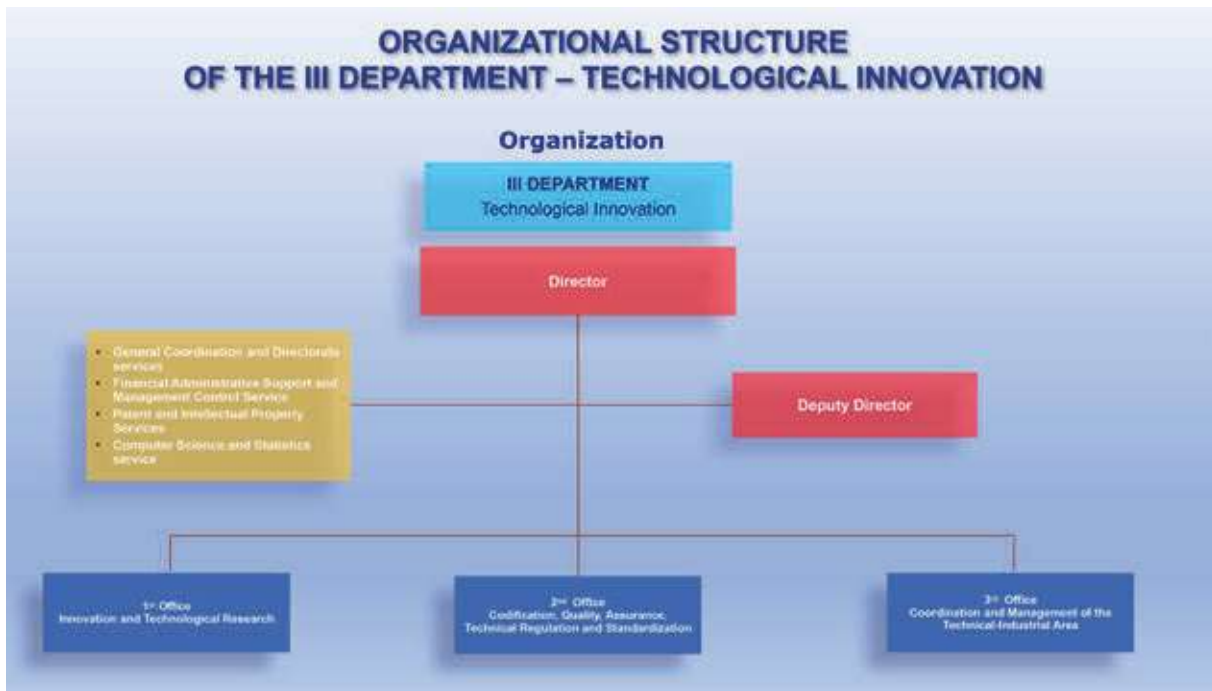




A LOOK AT THE ORGANIZATION



ORGANIZATIONAL STRUCTURE



The National Armaments Directorate (DNA), through the action of the III “Technological Innovation” Department, identifies, promotes and initiates, within the national and international cooperation sphere, technological research projects and programs (R/T) for Defense, the so-called “military research”. This occurs thanks to the activities and skills of the organizational units that make up the aforementioned Department, schematically represented in the figure above, including - in particular - the 1st Office, which, in various capacities, deals with research, experimentation and testing and related planning strategies.

This research activity includes a series of initiatives, primarily aligned with the criteria and indications of the Defense General Staff (SMD), which identifies the areas of primary technical-capability interest (the so-called clusters) towards which it should be oriented. Among these initiatives we find:

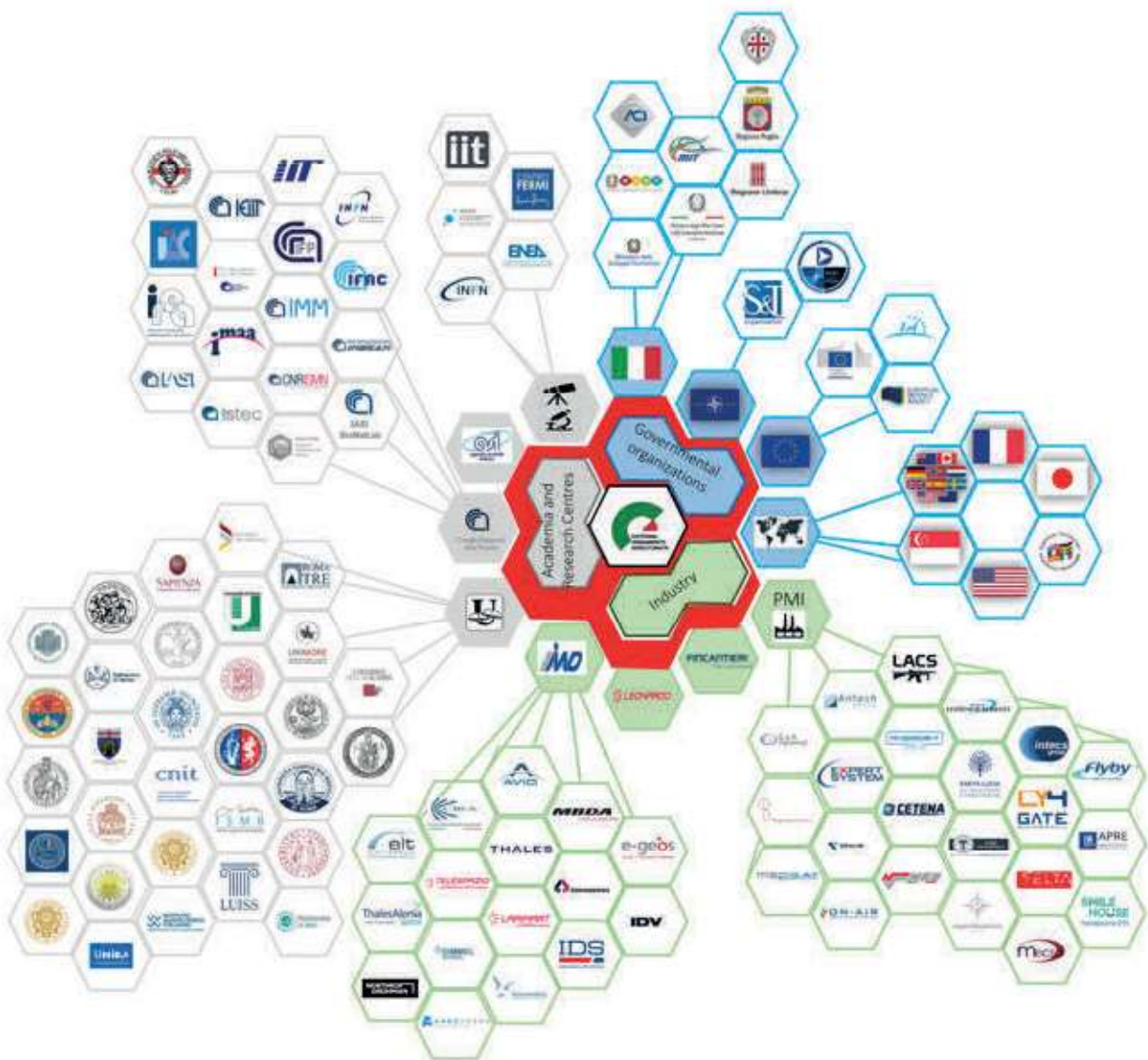
- the National Military Research Plan (PNRM), aimed at industries, small and medium-sized enterprises, startups, universities and national, public and private research bodies, with the aim of maintaining and enhancing national levels of excellence in specific technological sectors of interest to Defense.
- the technological research projects carried out at the Defense Test Centres, which aim to orient and strengthen Defense capabilities in the Test and Evaluation (T&E) sector.
- the Framework Agreements with Universities and research bodies, aimed at increasing the wealth of scientific and technological knowledge of Defense.
- international programmes, developed mainly within the EU (EDA - European Defense Agency and EDF - European Defense Fund), NATO (STO - Science & Technology Organization, DIANA - Defense Innovation Accelerator for The North Atlantic, NIF - NATO Innovation Fund) and bi-/multilateral.

THE NETWORK FOR TECHNOLOGICAL RESEARCH

THE EXTERNAL ORGANIZATION

The effectiveness of the innovation and technological research strategy implemented by the National Armaments Directorate is based on the creation and constant updating of a network of external relations with highly specialized, heterogeneous elements/organisations with diversified objectives,

which compete in a synergistic manner to achieve Defense guidelines in the field of innovation and research. This network of relations maintained by the National Armaments Directorate is divided into three cornerstones, namely governmental, scientific organizations (universities/academic and research bodies) and the industrial sector.



THE INTERNAL ORGANIZATION

An equally essential tool for identifying objectives, managing and exploiting knowledge is the internal organization of Defense relating to technological research, which can also be schematized according to three organizational cornerstones:

- the Defense General Staff and those of the Armed Forces (FF.AA.), oriented towards identifying the objectives of technological research and exploiting the results, with a view to the prospects of capacitive development;
- the Technical and General Directorates (DD. TT. and DD.GG.) of the National Armaments Directorate, indispensable for technical competence and project management;
- the Test Centers of the Armed Forces, an ideal test bed for the experimental validation and valorisation of the final results of the research activity, often consisting of technological demonstrators.



STRATEGIC OBJECTIVES

STRATEGIC OBJECTIVES

According to the Minister of Defense's Guidelines, the modernization of the military requires the support and harmonization of technological research, which should be geared toward achieving the Armed Forces' capability development objectives, synergistically involving all Defense entities involved in research, experimentation, and testing, both in development and operational settings.

The resulting strategic objectives of Defense scientific and technological research programs focus on various areas of intervention, aimed at identifying and protecting technologies deemed of "strategic value," ensuring national technological sovereignty and ensuring support for national projects or projects of national interest within European Union cooperation programs. This is achieved in collaboration with the defense industry, with the aim of maintaining and developing the sector's specific technological know-how, and involves collaboration with national and international industrial partners and the pursuit of synergies with research centers and universities.

To achieve these objectives, the strategy of the National Armaments Directorate, through the Third Department "Technological Innovation," is based on capability-pull and technology-push approaches and envisions coordination and collaboration between various organizations, such as Ministries, Research Centers, industry, and scientific institutions. The aim is to create a network of synergistic relationships for technological research, in collaboration with governmental, scientific, and industrial organizations.

The resulting technological research activities for Defense encompass various areas, such as the National Military Research Plan (PNRM), technological research and development projects conducted at Defense Test Centers, Framework Agreements with universities and research institutions, as well as international programs developed within the EU, NATO, and bilateral frameworks.

The priority areas for military technological research, fully consistent with Defense's capability requirements, include:

- C2 and Multi-Domain Situational Awareness: development of solutions capable of receiving, combining, and representing integrated data from military and civilian sensors and systems across the five operational domains (land, sea, air, cyber, and space), including information and electromagnetic environments, and ensuring the ability to plan and conduct multi-domain operations.
- Space Technologies: development of sensors/assets for the Detection, Mitigation, and Protection from new threats in the specific domain (Hypersonics, Anti-Satellite Systems - ASAT, Space-based Early Warning Missile); Military Satellite Communications – MILSATCOM (including the development of innovative narrow-band communication waveforms for operations in complex EM scenarios), Earth Observation, Access to Space, Responsive Space Capabilities, Space Domain Awareness (SDA), In-Orbit Servicing, Electromagnetic Spectrum Surveillance, Stratospheric Platforms.
- Cyber technologies: solutions for achieving situational awareness in cyberspace, for monitoring and defending Information Technology (IT) and Operational Technology (OT) systems in the battlefield/critical infrastructures on the national territory, as well as against attacks in the cyber domain. Technological solutions for countering Influence and disinformation activities in cyberspace. Technological solutions that exploit the electromagnetic spectrum to generate effects in cyberspace (Cyber Electro-Magnetic Activities - CEMA).
- Underwater: Technologies for controlling the underwater dimension, for the surveillance and protection of critical infrastructure (energy and communications sectors), and for the operational effectiveness of the vehicles and devices operating there.

- Urban warfare: Technologies for mapping, controlling, and exploiting the characteristics of urban areas and their subsoil, and for the operational effectiveness of the military vehicles and devices operating there (including Unmanned Systems).
- Cognitive warfare: Technologies and methodologies for the mitigation and exploitation of tools related to influence, interference, or alteration aimed at increasing or degrading the capabilities of the human mind.
- Artificial Intelligence: solutions supported by the use of Artificial Intelligence models in all its forms (statistical, logical, and semantic), including multi-agent.
- Technologies for the development and countering of Robotic Autonomous Systems (RAS) and Unmanned Systems (UxV) in all operational domains.
- Development of next-generation complex systems: development of directed energy weapons (laser and electromagnetic pulse - EMP) and defense systems.
- Enhancement of soldier operational capabilities: increased defensive and offensive capabilities (individual weaponry characterized by greater lethality and engagement capacity, exoskeletons, innovative and increasingly high-performance protective gear), increased energy autonomy for powering equipment and C2 supplies, human enhancement, advanced solutions for awareness, prevention, detection, and countering the CBRN threat, development of biosensors and bioelectronic applications for monitoring vital signs and combatant stress, and reduction of the negative effects of illnesses.
- Nanotechnologies, Novel Materials, and Manufacturing: development of high-performance materials resistant to extremely high temperatures and stress.
- Hypersonic Technologies: development of solutions relating to materials, propulsion systems, guidance systems, warheads, simulation of threat flight profiles (in order to identify their limits), sensors (space/aerospace, land and naval) and innovative actuators (or implementation of innovative solutions aimed at increasing the performance of existing actuators).
- Adaptation to the effects of Climate Change – Environmental sustainability, security and energy resilience, infrastructure efficiency improvement, adaptation of vehicles, systems, and equipment: solutions for reducing the logistical, environmental, security, and energy efficiency footprint of military infrastructure and assets.
- Next-generation communications networks: solutions supported by the use of 5G (including their integration with NTN - Non-Terrestrial Networks) and 6G technologies.

These sectors, which represent areas of strategic interest for military technological research and the modernization of Defense capabilities, align with the priority capacity-technological clusters identified annually with the Defense General Staff. The identification of these sectors allows for more effective and efficient planning and management of financial resources, reducing the fragmentation of technological research activities and the dispersion of resources across multiple and diverse initiatives.

This approach, which represents a strategic and organizational direction for National Armaments Directorate to constantly pursue, will help build a new shared mindset for Innovation within the CEO, aimed at continuously promoting an integrated military and civilian organization, an efficient incubator of new ideas and technical concepts for Defense.





RESEARCH IN THE NATIONAL CONTEXT



INTRODUCTION

In the context of the research programs conducted by the General Secretariat of Defense and National Armaments Directorate during 2024, the results of some projects are presented below

as they are considered exemplary of the technical-scientific activities, currently underway or completed, of relevance technology for the Defense and security sector:

- *Innovative 2-Cylinder Hybrid Diesel Power Unit* (**2CHDP**)
- Development of a coherent and distributed multiband radar system on a fleet of drones (**DISTIBUTED-DRONE**)
- Study for Mobile Multistatic Radar Network (**MoMuRaN**)
- Testing of a fifth-generation Cognitive Radio Distributor (**RADIC-5G**)
- Sensori su sistemi mobili e remoti Terahertz (**STORM**)
- Development of ATR methodologies based on convolutional neural networks (CNNs) (**PACMAN**)
- Design, construction, and testing of a biomimetic underwater robotic platform (**PERSICO**)
- *Self-Attentive Function Embeddings for embedded Systems* (**SAFE**)
- Conceptual design of the drone carrier vessel (**SCIAMANO**)
- *Wearable Assistant for VEterans in sport* (**WAVE**)
- Synthesis, Production of Ebselen and its Experimentation (**SPES**)
- Genotoxicity of electromagnetic radiation in military applications (**GREAM3**)
- Genomic Analysis of Resistoma Nosocomial Infections in Operating Theaters (**AGRINTO**)
- Development of a demonstrator of a ship-based launcher extraction system (**SIMONA**)

The research project by Oral Engineering, named PNRM “2CHDP Project and Development of an innovative 2-cylinder hybrid Diesel propulsion unit,” aims to develop a technological solution for the hybrid propulsion of light military vehicles.

The activity involves the design, construction, and development of an innovative hybrid powertrain (diesel + electric) consisting of a 2-cylinder thermal engine with dual injection and high power density, coupled with an axial flux electric motor with a high power-to-weight ratio.

The motor-generator unit can also be used as a generator set or propulsion unit for boats. Possible usage scenarios on a vehicle include silent mode (electric only) for operational or reconnaissance missions, with autonomy dependent on battery capacity, power of 170 HP, silence, low thermal traceability, and zero emissions. Thermal mode, with power of 235 HP and autonomy dependent on fuel tank capacity; hybrid mode with total power of 380 HP; use as a Range Extender to recharge the vehicle’s traction batteries; use as an APU generator set to produce electrical energy in a base camp, powering all electrical/electronic devices.

This project represents a significant advancement in light military vehicle technology, offering versatile and high-performance solutions for various operational needs.

INTRODUCTION

In recent years, diesel engines used in military vehicles have distinguished themselves from those used for freight transport due to the need for greater power and torque. Additionally, there is a growing demand for hybrid propulsion vehicles, while keeping the weight and dimensions of the propulsion unit contained.

The research project by Oral Engineering aims to provide a technological and operational solution for the hybrid propulsion of light military vehicles, characterized by high power density, reduced displacement, low weight, and low fuel consumption.

The hybrid unit designed by Oral Engineering consists of a two-cylinder thermal unit with a total displacement of 2600 cc, developing a maximum power of 173 kW (235 HP), and an electric unit of 125 kW (170 HP). The common rail in-

jection system, with dual injectors per cylinder (Oral patent), is paired with an engine control unit (ECU) developed by Oral in collaboration with an Italian company.

The dual injection patent will allow future exploration of the use of various types of green fuels, such as diesel and gasoline, diesel and hydrogen, and e-fuels.

TECHNICAL BACKGROUND

In recent years, operational scenarios have highlighted the need for hybrid vehicles with high power density and the ability to operate in silent mode. The PNRM 2CHDP project anticipates this trend, based on the design of a two-cylinder Diesel engine coupled with an axial flux electric motor, suitable for a wide range of applications.

Oral Engineering’s experience in engine design, along with valuable information provid-

ed by Armed Forces operators, has allowed for the precise definition of the optimal characteristics of the hybrid unit, ideal for light and medium vehicles.

METHODOLOGY

The project's methodology focused on analyzing the propulsion systems used in "Light and Medium Duty" military vehicles and evaluating hybrid and multi-fuel technologies (diesel, hydrogen, LPG, biofuels, e-fuels) applicable in the medium term in both civilian and military sectors. A key element is the common rail injection system with dual injectors per cylinder, patented by Oral, which optimizes these applications.

The strategic approach transferred automotive know-how on next-generation hybrid powertrains to military propulsion systems, integrating management and control methodologies for the two units. The technological core is the coupling of a high power-to-weight ratio electric motor/generator with a newly designed internal combustion unit, powered by diesel. This layout combines the benefits of electric propulsion (silence, low ther-

mal traceability, zero emissions) with those of advanced diesel engines.

The project, structured in three phases of 12 months each, included:

Phase 1.0 (2021): Concept development, technological and patent analysis, preliminary sizing of thermal and electric units, 3D design of the thermal engine, combustion calculations, and CFD/FEM analysis of main components (cylinder head, piston, crankshaft, engine block) (Figures 1,2,3,4,5,6).

Phase 2.0 (2023): Simulation and development of electronic control through the Oral common rail system, design of injection management software, construction of control units (ECU), sizing of the turbocharging group, and creation of technological demonstrators (DTA) (Figure 7).

Phase 3.0 (2025): Assembly of DTAs, bench calibration with data acquisition, durability tests, and definition of final power curves.

This approach ensures effective integration of innovative technologies for advanced military propulsion systems, with cross-sector applications to the civilian sector.

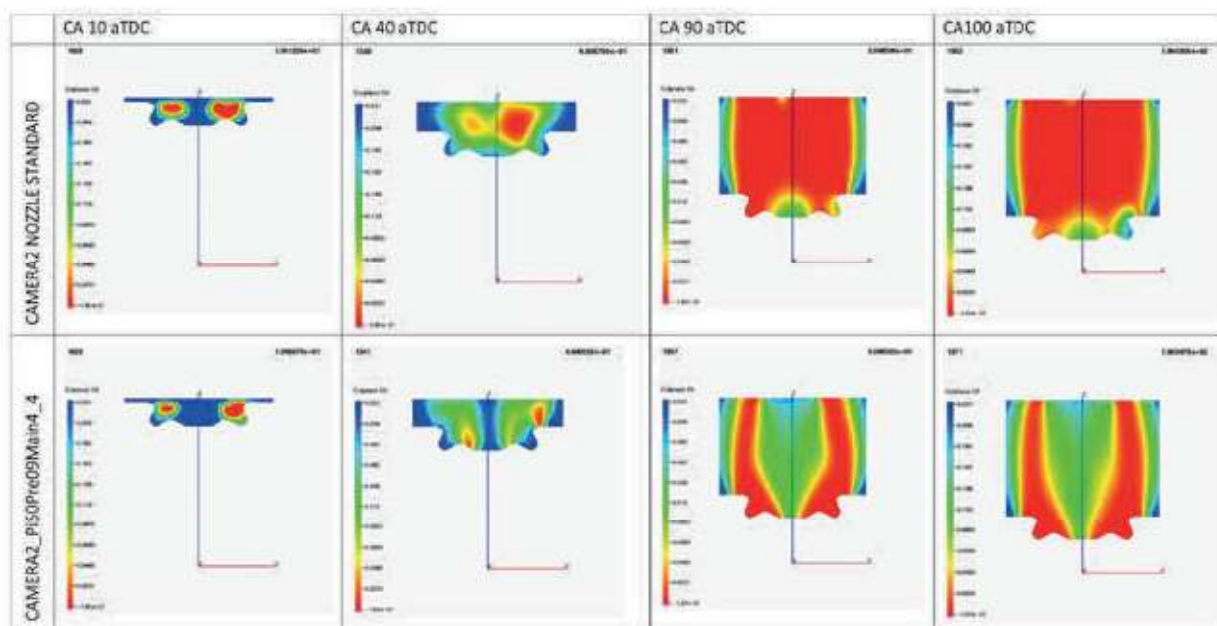


Figure 1 - CFD combustion analysis.

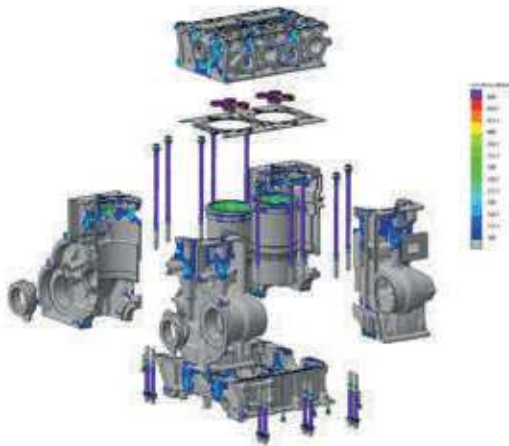


Figure 2 - FEM Structural analysis.

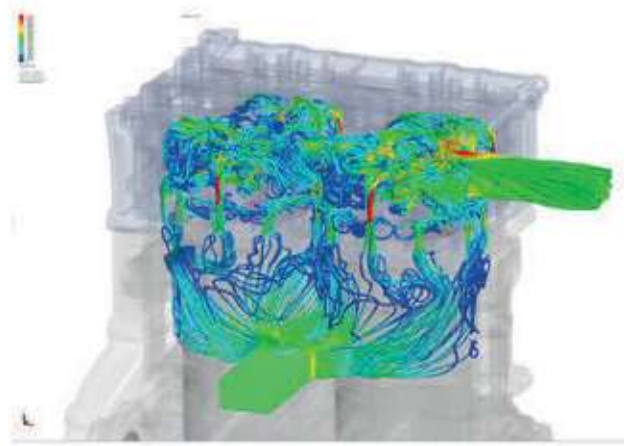


Figure 3 - CFD cooling system analysis.



Figure 4 - Overall dimensions of the 2CHDP hybrid group.

Common-rail system CRS2-25

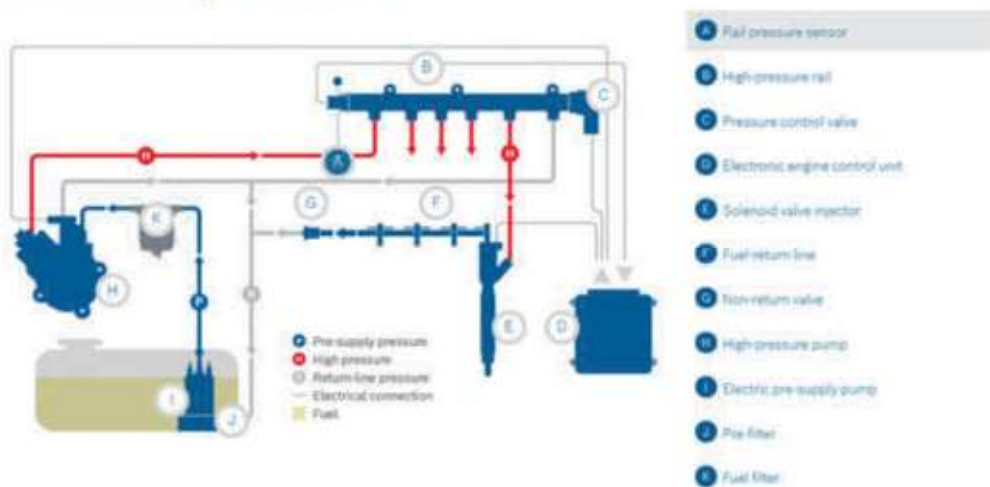


Figure 5 - Common-rail injection circuit with double injector per cylinder.

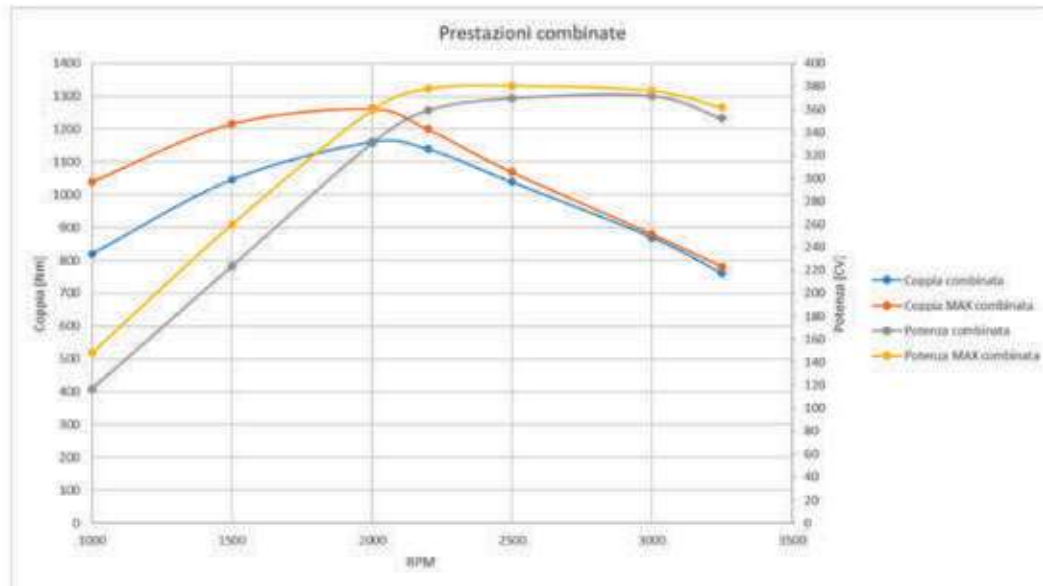


Figure 6 - Combined performance of the 2CHDP hybrid group.



Figure 7 - Assembled engine ready for test bench.

POTENTIAL TECHNOLOGY APPLICATIONS AND EXPLOITATION

At the end of PHASE 3.0, the hybrid unit will be ready to be installed on a vehicle for road

testing. In collaboration with AD, Oral will contact a national manufacturer to evaluate the possibility of setting up a hybrid experimental vehicle to be tested on a specific test track. The dimensions of the new two-cylinder thermal engine, together with the electric unit, are comparable to those of the current four-cylinder thermal engines used in this type of vehicle. Additionally, the hybrid unit can be immediately used as a generator set (APU), capable of providing power of approximately 120 kW, with weights and dimensions 50% lower than current production units.

CONCLUSIONS

The technology introduced in the hybrid unit project (thermal engine + electric) is framed within a broader perspective than the design of a single two-cylinder propulsion unit. It aims to create an entire family of propulsion units, which, according to a modular logic, can meet the needs of a wide range of vehicles (Light, Medium, and Heavy Duty), ensuring high component interchangeability and facilitating logistical and maintenance operations.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

AD	<i>Amministrazione Difesa</i>
APU	<i>Auxiliary Power Unit</i>
CFD	<i>Computational Fluid Dynamics</i>
DTA	<i>Dimostratore Tecnico Avanzato</i>
FEM	<i>Finite Elements Method</i>
PNRM	<i>Piano Nazionale Ricerca Militare</i>

KEYWORDS

Twin-Cylinder, Hybrid, Diesel, Powertrain.

PROJECT INFORMATION

PNRM number:	a2018.153
Organization:	Direzione Armamenti Terrestri
Responsible entity:	Oral Engineering S.r.l.
City, Region:	Baggiovara (Mo), Emilia Romagna
Project lead:	Sig. Franco Antoniazzi
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DISTRIBUTED-DRONE

The project aim is to develop a multi-band multistatic radar system operating on a fleet of drones that implements coherent signal fusion, allowing a higher resolution than non-coherent radar systems. The novelty consists in the use of photonics as an enabling technology, which allows to distribute coherent signals to peripherals without complex synchronizations. The final goal is to realize a small-scale demonstrator using integrated photonic circuits where necessary. Phase 1 aimed at studying the system, its optimization through numerical analysis and design including integrated photonic circuits. The activity was developed by performing an analysis of the scenario, definition of the requirements and definition of the key system parameters, followed by the optimization of the architecture. Then the algorithms are defined and the hardware designed, identifying two solutions. A multi-monostatic prototype with two sensors, one for each drone, based on a simplified hardware that does not require technological developments, suitable for a technology transfer in the short term. The other solution is a multiple-input multiple-output coherent prototype with three fixed sensors to be installed in the laboratory. This design allows to demonstrate the potential of a coherent distributed system and to advance the development of integrated photonic technologies.

INTRODUCTION

The increasing demand for surveillance systems with high resolution, flexibility and adaptability to various military or civil operational scenarios has driven the advancement of radar technology in architectural aspects and processing capacity. In this context, radar systems have rapidly evolved from fixed platforms to mobile airborne platforms and recently to drone-borne configurations, marking a shift towards more flexible, affordable and high-resolution approaches for different operational environments. A single drone radar has reduced performance if the target has an equivalent radar cross-section low or with a large angular variability. Furthermore, there are limitations in resolution in the direction perpendicular to the signal propagation (cross-range), sensitivity, robustness to shadowing phenomena. To overcome these limitations, radars on multiple drones, i.e. multistatic systems, can be exploited, but the fusion of in-

dependently acquired data limits the benefits. In this project, an approach to overcome these limitations is proposed, based on a coherent multi-band multiple input-multiple output (MIMO) system with centralized processing of raw data, enabled by photonic technologies. The use of integrated photonic technologies allows for the creation of compact payloads, making the system usable on drones.

TECHNICAL BACKGROUND

Currently, the use of radar on drones is limited to independent monostatic radars [1]. This limits the cross-range resolution. Recent studies are focused on MIMO radar systems on drones that employ multiple antennas, achieving a high signal-to-noise ratio gain and overcoming the limitations of monostatic systems. MIMO systems are divided into co-localized [2] or distributed systems [3]. The former are the most studied and offer two-dimensional imaging by

exploiting interferometric techniques that use a single frequency, with limitations in sensitivity and resolution and criticality with respect to the variation of the target reflectivity. Recently, distributed MIMO radar configurations with high level of cooperation have been proposed that can ensure better localization accuracy, spatial resolution, robustness against shadow zones and stealth target detection capabilities. These systems require high-capacity communication links to send raw data from the antennas to the central processor, precise synchronization and high phase coherence between all components. A solution using electronic devices is very difficult.

Photonics enables coherent multiband distributed radars and allows the generation and processing of multiple radar signals in different bands through a single local oscillator, ensuring coherence between the signals [4][5]. The signals can be generated in a single central unit and distributed to multiple antennas via optical fibers or free space links. Furthermore, photonics ensures phase noise stability and optical links allow higher bandwidth and lower sensitivity to interference compared to radio links. Experiments and preliminary analyses of distributed MIMO systems are demonstrat-

ed on fixed platforms [6]. Regarding integrated photonic technologies, the components and subsystems needed for the implementation of a distributed MIMO radar system have already been realized on chips [7]. The implementations have shown a low efficiency that can be overcome using hybrid integration.

METHODOLOGY

Coherent, non-coherent and multi-monostatic MIMO processing algorithms were implemented, building the system simulator. The drones' position was optimized by varying the design parameters, identifying the potential of the different algorithms. The resolution of the coherent MIMO system is an order of magnitude higher than the design specifications that can be achieved also with a simpler multi-monostatic approach. The analysis with respect to non-idealities highlights how coherent MIMO is extremely sensitive to inaccuracy in drone positioning, even with a few millimeters of error. The non-coherent MIMO and multi-monostatic approaches are much more robust, tolerating inaccuracies of a few centimeters. The architecture design followed two approaches (Figure 1): multi-monostatic system distributed on drones and coherent MIMO system distrib-

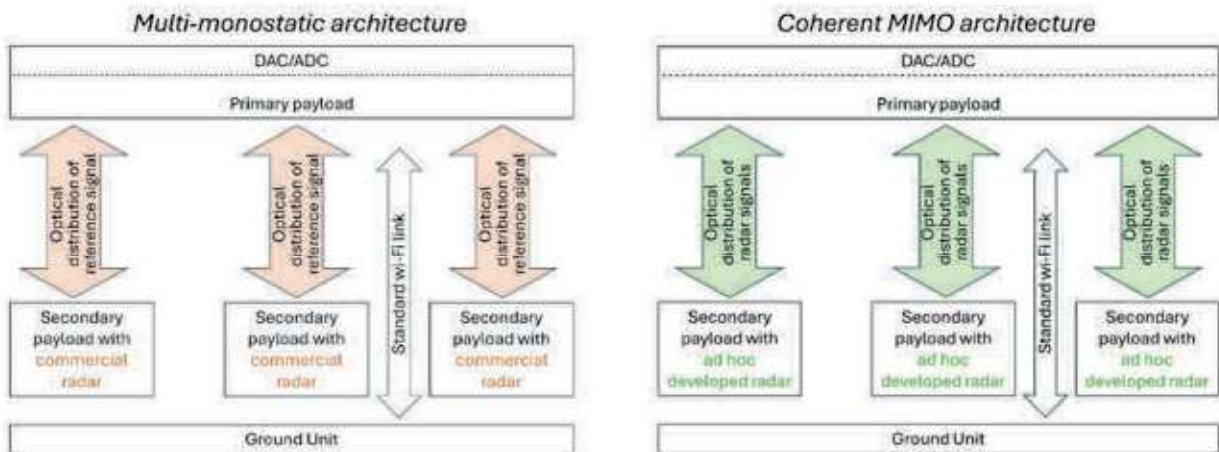


Figure 1 - Left: Multi-monostatic architecture based on clock signal distribution and commercial radar cards. Right: Coherent MIMO architecture based on direct distribution of radar signals.

uted on fixed platforms and hardware suitable for drones. The first approach is less complex and maximizes robustness, allowing a rapid technology transfer. The second develops advanced technological solutions that maximize the benefits of coherent MIMO, overcoming the limitations of the unavailability of sufficiently precise positioning systems for drones. An optimization of the two systems was carried out as a function of the number of drones, the geometry of the system for linear and square arrangements, the type of signals, the use of radar bands. The use of dual bands does not

offer significant improvements in resolution, but helps in identifying stealth targets. The hardware of the two prototypes was designed, defining the power budget. For the integrated optical circuits, two approaches were considered: an innovative one based on hybrid integration of circuits made with Indium Phosphide (InP) and Lithium Niobate on Insulator (LNOI) technology, another based on monolithic InP integration, more mature but with slightly lower performance. The specifications of the proposed solutions substantially satisfy the design specifications (Table 1).

Table 1 - Comparison between the values of the identified architectures and the project specifications.

	Multi-monostatic architecture	Coherent MIMO architecture	Project specifications
Parameter	Value	Value	Value
Number of sensors	2	3	3
Supported RF carriers	60 GHz, 24 GHz	2 carriers in X and Ka/V band (photonic integration)	2 carriers in X and V band
Total instantaneous bandwidth	2 GHz (V band), 120 MHz (Ku band)	≤ 2 GHz	≤ 2 GHz
Target distance	≤ 50 m	≤ 50 m	≤ 50 m
Resolution cell size	$\leq 10 \times 10$ cm	$\leq 10 \times 10$ cm	$\leq 10 \times 10$ cm
Payload size	$\leq 40 \times 40 \times 40$ cm	$\leq 40 \times 40 \times 40$ cm (primary)	$\leq 40 \times 40 \times 40$ cm
		$\leq 40 \times 40 \times 40$ cm (peripheral)	
Payload weight	≤ 2.04 kg	≤ 6.4 kg (primary)	≤ 10 kg
		≤ 1.5 kg (peripheral)	
Maximum power consumption	≤ 17.9 W (components off the shelf)	≤ 3.3 W (Hybrid PIC InP/LNOI)	≤ 12 W (for PIC)
		≤ 1.8 W (monolithic PIC InP)	

POTENTIAL TECHNOLOGY APPLICATIONS AND EXPLOITATION

The distributed radar system on drones finds application in the military and civil fields in the monitoring of medium-small areas with high spatial resolution (few centimeters) and allows for example detecting people, small vehicles or boats and to map, using imaging techniques, the terrain and buildings, for example after natural disasters. The system has the advantages of a conventional monostatic radar, i.e. it can operate with and without sunlight, in the presence of fog, rain and reduced visibility, to which are added the advantages of a coherent distributed MIMO system, such as high resolution, robustness with respect to shadowed and stealth targets. Since the system can be deployed on small mobile platforms such as drones, it can be easily transported where necessary, without need of fixed infrastructures on the ground, and therefore also in emergency situations. The development of integrated photonic technology for distributed coherent radar is a central part of the research activity and the bodies involved in the project have been carrying it forward for many years, gaining a lot of experience. The development of InP and LNOI technologies in this project will allow to increase the maturity level of distributed MIMO radar systems for mobile platforms.

CONCLUSIONS

In Phase 1, a numerical analysis was performed that led to the design of two prototypes of a distributed radar system for drones. A multi-monostatic prototype on two sensors arranged in line, with simplified hardware. A coherent MIMO prototype on three sensors arranged in line to be installed on fixed platforms in the laboratory. The latter will allow demonstrating the potential of a distributed coherent MIMO system and advancing the development of integrated photonic technologies. The coherent MIMO approach has a resolution much higher than that estimated in the proposal, but presents high sensitivity to vibrations that requires a drone stabilization with sub-millimeter precision. The non-existence of such precise stabilization systems nowadays, makes only a laboratory demonstration possible to date. The multi-monostatic approach is simpler from an implementation point of view and does not allow the high resolution of the coherent MIMO system, but still achieves the project performance with high architectural robustness. This solution would be implementable with commercial products and would not require technological developments, making the system suitable for immediate technology transfer. The two solutions could be carried forward in parallel in the subsequent Phase 2 of the project which includes the implementation of the systems.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

InP	<i>Indium-Phosphide</i>
LNOI	<i>Lithium Niobate On Insulator</i>
MIMO	<i>Multiple-Input Multiple-Output</i>

KEYWORDS

Photonic radar, distributed radar, coherent MIMO, integrated photonic circuits, LNOI, InP.

PROJECT INFORMATION

PNRM number:	a2021.216
Organization:	Direzione Armamenti Terrestri
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The project concerns the technological area of mobile multistatic radar networks for air surveillance applications in urban environments using innovative techniques regarding multistatic processing, radar and communication waveform generation and synchronization of the transmitting and receiving system. The operational framework of reference is currently characterized by an increasing complexity and uncertainty, outlined by conflicts characterized by congested maneuver spaces but above all the severity about the air defense radar point of view, such as represented by the urban ones, in which each military action presents high tactical and threat dynamics.

In the development and validation of the technologies, the radar mobile network architecture foresees a single transmitting radar and multiple cooperating receiving radar nodes, that for the exchange of information and controls a bidirectional communication and synchronization Radio Frequency data links is needed. After Phase 1 study regarding the operational concept and the simulation of the radar techniques used, the use of Breadboards and a technological demonstrator for AESA radar evaluation is planned.

Significant results concern multistatic radar techniques using communication signals, for the detection of slow and low-altitude targets such as drones, using Software Defined Radio processing platforms.

INTRODUCTION

The Phase 1 study together with the Armed Forces defined the performance characteristics and operating protocols of the network for its dynamic reconfigurability, also developing the fundamental components that, through the same hardware, allows for RF (Radio Frequency) data transmission used as a radar waveform for use on UGVs (Unmanned Ground Vehicle). This opportunity, in addition to not requiring separate communication hardware, does not even require a different setting to work. The delocalization of the transmitter with respect to the receivers dramatically reduces the probability of interception, also enhancing the detection capabilities of stealth targets, especially in urban environments. This also implies a reduction in the manufacturing cost of the component modules, as well as reducing the problems of possible cooling and high power absorption, installation and cost.

The project uses a synchronization technique for cooperating radar nodes, making use of digital modulation techniques typical of wireless communications, with the possibility of extending the field of use of the radar itself in both the military and civil fields. A dual value is in the detection of unauthorized UAVs (Unmanned Air Vehicle) used for civilian applications, masked behind infrastructure, with communication failure or confused in multiple swarms of drones.

TECHNICAL BACKGROUND

The evolution of the type of conflict related to the use of UGV and UAV systems requires the satisfaction of the requirement of improving Situational Awareness. This is possible through a network of cooperating radars that can guarantee surveillance for air defense and at the same time, through the same RF device, carry out data transmission. The objectives of the missions will change in real-time and rapidly. Consequently, the

use of radars will have to guarantee a capillary volumetric coverage variable in space and time even in urban environments and with target localization accuracies adequate to the use of the effectors used. A multistatic radar network on UGVs for surveillance and communication will therefore allow a significant improvement in the range and Low Probability of Intercept (LPI) characteristics. In a multistatic coherent radar system, composed of delocalized transmitters and receivers, the synchronization functions of the transmitted and received waveforms are the most important and critical of all the components. The reason for the importance and implementation difficulties is linked to the interaction with the real transmission channel which, for a mobile system, is typically time (fading) and space variant (obscuration and multipath). The sensor network will therefore be multifunctional, i.e. supported by a communication system via dual and interactive RF link for the exchange of information between radar nodes aimed at real-time optimization of both surveillance and tracking performance, node control and tactical operational performance. In a time-variant random topology network, knowledge of the quality level of real-time synchronization and its control is essential for obtaining system performance and the mission itself. Furthermore, the synchronization system must provide for the possibility of a tampering or spoofing attack, and therefore must maintain the holdover capacity, through the use of alternative solutions based on different synchronization techniques.

METHODOLOGY

During the first phase of the project, in Technical Report D1.1 – “The Operational Concept and Preliminary System Requirements”, a conceptual framework was provided to define the objectives and directions for the creation and maintenance of a relevant and effective tool, fully integrated into the Army’s operations. Figure 1 shows an example of disrupting en-

emy operations using an integrated sensor network. In Technical Report D1.2 – “Simulations

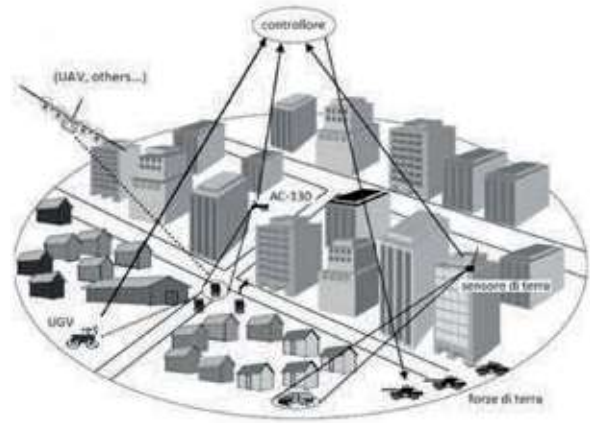


Figure 1 - Example of an enemy disruption operation using a sensor network.

and Breadboards: Synchronism, RadCom and Multistatic Processing (first version)” a framework was provided for the techniques identified as the technological pillars of the Project, such as Synchronism, the RadCom technique and Multistatic Processing.

- Synchronism

A state-of-the-art analysis of wireless channel synchronization in complex radio scenarios has been conducted in order to ensure a sufficient level of robustness and minimize the time required for the transmission of timing information.
- RadCom technique

A waveform which is capable of allowing both the transmission of information and radar surveillance simultaneously to be used has been defined. The study has been focused on the design of the OFDM (Orthogonal Frequency Division Multiplexing) waveform, shown in Figure 2, which is a particularly appropriate choice for the design of sensors that integrate radar and communication functions.

The identified functional blocks (waveform simulator, operational scenario simulator, radar processing block, communications processing block) were implemented in Matlab.

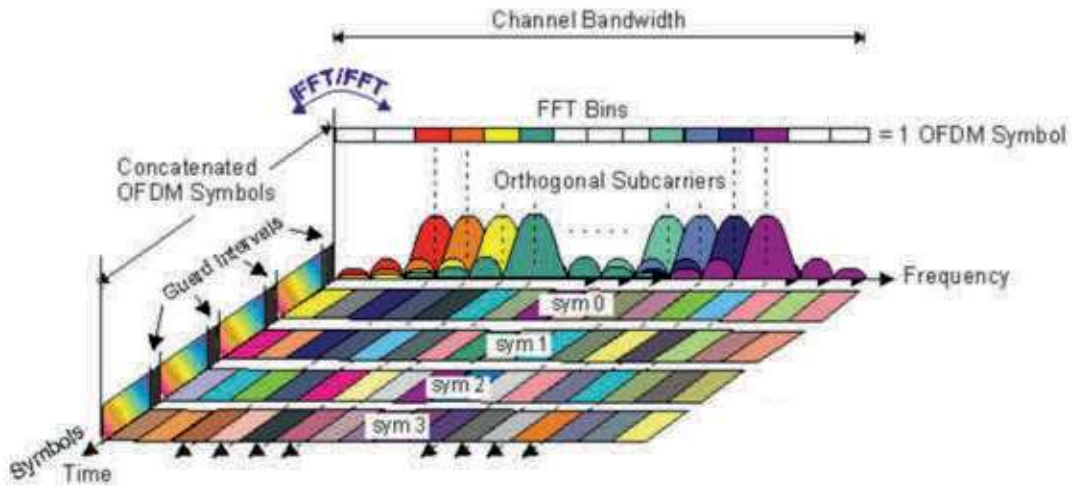


Figure 2 - Time-frequency representation of an OFDM waveform.

- Multistatic Processing (first release)

An accurate review of the state of the art regarding target detection techniques through radar networks in an urban environment has been presented as well as the description of the information processing and fusion techniques (Plot Extractor) coming from a sensor network, in order to appropriately process the acquired data in a centralized mode. Figure 3 shows how multiple sensors can identify target 1 separately from target 2 compared to using a single sensor. Finally, the specifications for the purchase of Breadboards necessary for the development and validation activity for the following years have been defined.

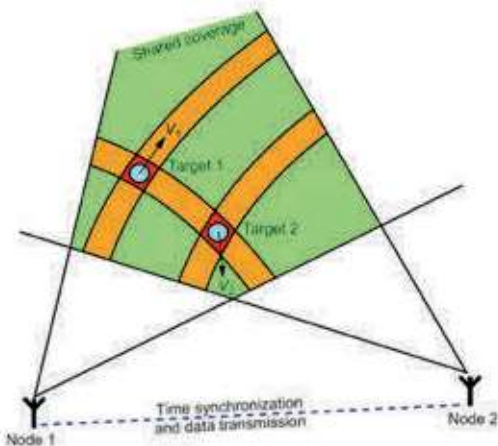


Figure 3 - Multistatic Processing Example.

POTENTIAL TECHNOLOGY APPLICATIONS AND EXPLOITATION

The technological solutions are and will be studied, discussed and shared by Rheinmetall Italia with the contribution of CNIT, the University of Naples “Federico II” and the University of Rome 1 “La Sapienza”. The innovation activities are managed by the “Research Innovation & Technology” area of Rheinmetall Italia. The strategic approach to the use of the technologies adopted is based on the principles of Strategic Design which aims to identify the right trade-off over time, between user requirements, technological feasibility, product diversification, cost and economic sustainability. This involves the continuous development of prototypes, breadboards, technological demonstrators and the progressive review of the requirements, which allows for the development of future solutions based on the real needs of the Armed Forces in using the proposed system. During the project development, continuous evaluation processes of the technological solutions adopted are activated, to verify their real effectiveness, taking into account factors such as risk, evolutionary trajectory over time and technological convergence. In this process the Armed Forces are considered an integral

part of the project team and actively participate in all the design phases contributing to the identification of the solutions that are gradually implemented.

CONCLUSIONS

The project involves the study of the technologies and techniques of the technological pillars of a mobile multistatic radar network using a digital telecommunication waveform for the simultaneous transmission of data and radar surveillance in urban environments. These have major applications in short-range and low-altitude air surveillance, in particular for use on UGV platforms in propagatively complex operating environments, especially for stealth targets and drones as in the urban environments.

The aim is to study, simulate and experiment on Breadboard the techniques related to the mobile aspect of the multistatic network, the RadCom technique and the synchronization system, in order to identify the limits as well as the advantages for addressing the design of a future product.

The architecture includes a single transmitting radar and multiple cooperating receiving radar nodes, with the related RF data links for the exchange of information and controls.

The activity is based on bibliographic studies and laboratory experiments benefiting from modern modeling and fast prototyping methodologies, based on Commercial Off The Shelf components (COTS). The use of commercial evaluation boards and a radar technology demonstrator is planned for concept validation.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

AESA	<i>Active Electronic Scanned Array</i>
COTS	<i>Commercial Off The Shelf</i>
FFAA	<i>Forze Armate</i>
LPI	<i>Low Probability of Intercept</i>
OFDM	<i>Orthogonal Frequency Division Multiplexing</i>
RADCOM	<i>Radar and Communication</i>
RF	<i>Radio Frequency</i>
SDR	<i>Software Defined Radio/Radar</i>
UAV	<i>Unmanned Air Vehicle</i>
UGV	<i>Unmanned Ground Vehicle</i>

KEYWORDS

Multistaticity, RADCOM, Synchronization, OFDM, Radar, Urban Warfare, Software Defined Radar, Radar Sensor Network.

PROJECT INFORMATION

PNRM number:	a2020.280
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Rapporto Tecnico D1.2 “Il Concetto Operativo e i Requisiti Preliminari di Sistema”, Progetto di Ricerca Tecnologica.

The RADIC-5G project aims to improve the effectiveness of reactive jammers. The project optimizes the ES (Electronic Support) component, necessary for detection and identification (for example of UAS).

Aspects relating to broadband radio direction finding are explored in depth, which are particularly important due to the growing threat linked to the use of latest generation drones (both aerial and terrestrial), which use sophisticated communication and navigation protocols.

The project claims several innovative aspects, including the introduction of an Electronically Steered Antenna (ESA) and a pure wide-band interferometric system (compared to the state of the art of correlative interferometric systems), the use of a 4-channel SDR with an instantaneous bandwidth of 200 MHz, sophisticated calibration algorithms, usable during the operational phase, and finally the classification of all signals simultaneously present in the instantaneous bandwidth, measuring their S/N ratio, occupied bandwidth and angle (with an accuracy better than 1° rms), all using a single, very compact antenna system for the 400 MHz to 6 GHz band.

The project has shown that it is possible to integrate goniometric functions (ESA antenna and/or interferometric system) and wideband signal analysis functions in the current generation of reactive jammers, using the SDRs developed for 5G, implementing powerful signal processing algorithms on many synchronized channels. The improved ES allows to operate in the presence of multiple emitters and with variable electromagnetic propagation (vehicular application and/or urban scenarios), and brings benefits to the EA (Electronic Attack) functions, allowing to optimize the detection thresholds, distribute the power in case of multiple targets and choose the most appropriate waveform.

INTRODUCTION

The direction of arrival (DoA) of a received signal can be obtained by switched directional antennas (ESA) or by an interferometer. An interferometer is a system that measures the direction of arrival (DoA) of a received signal, based on the relative phase measured between the various elements of an antenna system.

Phase-based DoA is very reliable as the amplitude of an electromagnetic wave presents fluctuations due to propagation, while the phase remains essentially unchanged, and is not influenced by the dynamics of the received signal. The application of interferometry concerns

many areas (for example, it is widely used in radio astronomy) and there is a large literature on the subject. Military applications are often based on subsystems of five antennas switched on two channels [1]. The project instead uses four channels using SDR technology developed for mobile telephony (MIMO etc.).

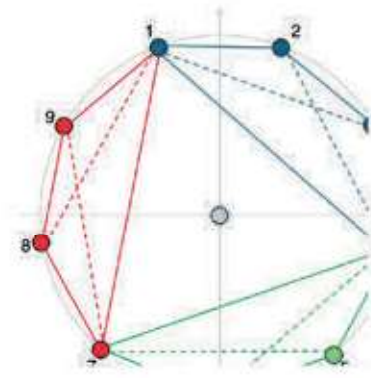
The state of the art typically refers to single narrowband signals, while the current design considers multiple broadband signals (e.g. LTE or WiFi) that may be present in an RF band. The intended application is mainly to determine the DoA of drones, based on their emissions, however the study can easily be extended to oth-

er signals, for example mobile phone signals. The developed technology is applied both in the military field (multi-domain Cyber and Electromagnetic Activities (CEMA)) and in the civil field (protection of prisons, anti-UAS systems for large events, etc.).

TECHNICAL BACKGROUND

The requirements of a DF antenna subsystem concern the number of elements, the RF band to be covered and the desired measurement accuracy. In an interferometer, a wide spacing of the antenna array is required if a high sensitivity is to be achieved [2]. However, the wide spacing introduces ambiguities, especially at high frequencies (wavelength of a few centimeters), which can only be solved by using bases with various spacings [1][3][4]. Furthermore, antennas have a physical size, and cannot be placed too close together, otherwise unwanted interactions are created (Antenna Mutual Coupling).

The designed array, based on nonlinear layout, is illustrated in Figure 1. The array can be considered a “uniform circular array” (UCA) [5]. This is an enneagon geometry, where nine receiving antennas are positioned along the circle, and a tenth antenna used for calibration is placed in the center.



METHODOLOGY

The project uses the latest generation SDR. The FFT processing allows to realize a channelized direction finding architecture, isolating the contributions coming from multiple signals. However, the FFT shows phase errors due to sampling (generally “non-synchronous” i.e. the sampling frequency is not a multiple of the signal frequencies). The “all phases FFT” (apFFT) was introduced in [6], and successfully implemented in the project.

The signals emerging from noise are discriminated based on the spectral separation. Angular measurement is done on these signals, based on the estimate of the phase difference on each of the eighteen bases ($\Delta\phi$), of aperture d , obtained in 3 switching cycles. The $\Delta\phi$ is given by:

$$\Delta\phi = \left(2 \pi \frac{d}{\lambda} \right) \sin\theta$$

The phase measurement gives a unique result in the case in which $\Delta\phi$ is in the interval $(-\pi, +\pi)$ with the direction θ of the arrival signal in the interval $(-90^\circ, +90^\circ)$, and the following relation holds:

$$d \leq \frac{\lambda}{2}$$

If instead $d > \lambda/2$, as in our case, in which the band reaches up to 6 GHz ($\lambda = 5$ cm), the $\Delta\phi = f(\theta)$ curves have the behaviour shown in Figure



Figure 1 - The enneagon antenna array developed for the project. Eighteen bases are used (in 3 groups of six), each consisting of a pair of antennas. The chosen geometry allows for easy mounting of the antennas on a military platform, such as a tactical vehicle or the mast of a ship.

2, and almost 4 octaves of frequency can be covered with a single antenna subsystem only solving the ambiguities (a $\Delta\phi$ corresponds to N possible angles):

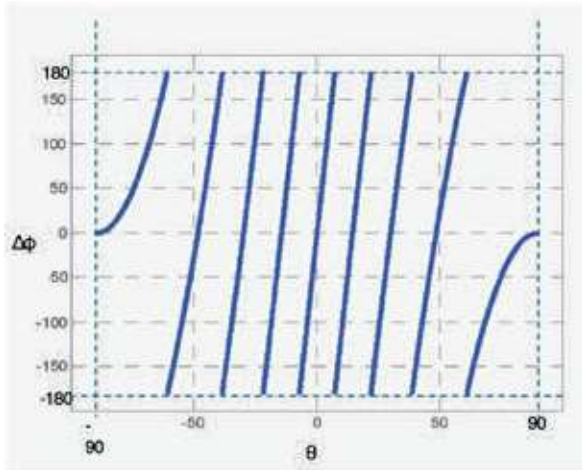


Figure 2 - base diagram, curves $\Delta\phi = f(\theta)$, relates phase differences to the angles from which the signal is received. From the figure we can see that each measured $\Delta\phi$ (on the ordinate) corresponds to a set of possible angles θ_i (on the abscissa).

With four receiving channels we can calculate six $\Delta\phi$, as shown in the following example. Figure 3 shows the angles formed by a signal (tone, 2461 MHz) positioned 175° with respect to base 1-2, for the six bases.

The four phases measured, on the peak values of the signal, for the four channels, are $\phi_1: 105.37^\circ$, $\phi_2: 147.83^\circ$, $\phi_3: 62.19^\circ$, $\phi_4: -15.73^\circ$.

The six measurements (3 with short base and 3 with long base) are shown on the phase diagrams ($\Delta\phi$ vs. θ) in Figure 4 (based on a priori knowledge of the direction of the test signal). There is a good agreement between the measurements and the theoretical values, which means that the system has been well calibrated.

A complete analysis of interferometry, with particular attention to the ambiguity resolution problem, has been developed in [7]. The main result of the present project consists in the development

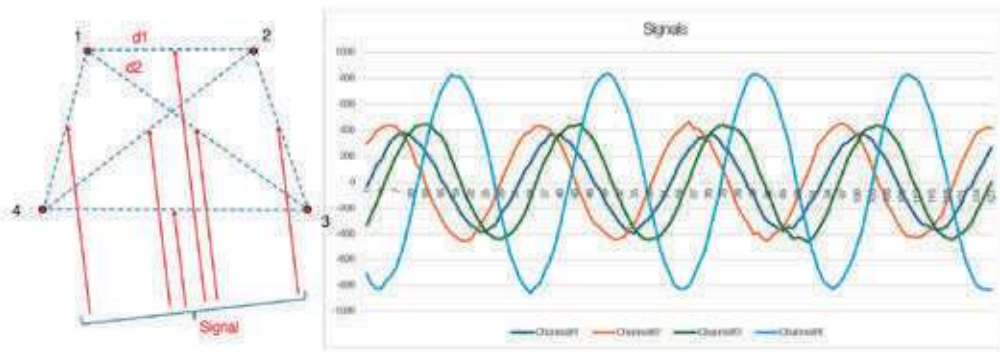


Figure 3 - Example of DoA measurement with 4 antennas and 6 phase differences $\Delta\phi$.

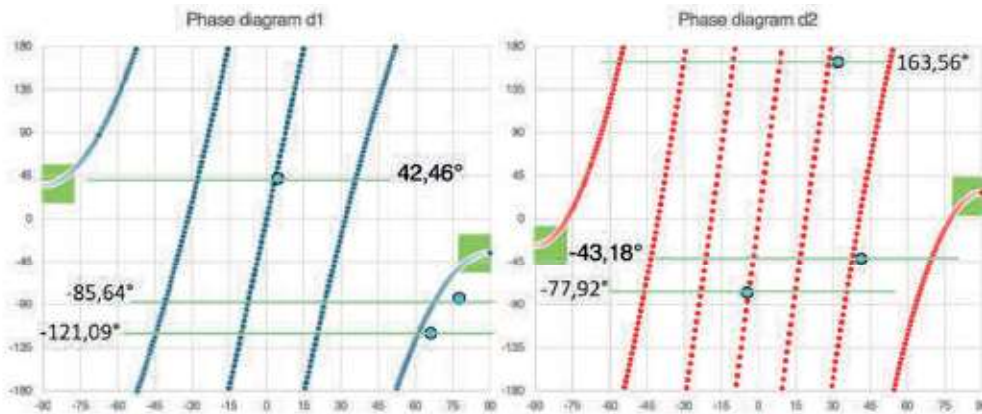


Figure 4 - Representation of $\Delta\phi$ on phase diagrams. It is important to note that there are critical zones in the phase diagrams (highlighted in green), where small changes in estimates of $\Delta\phi$ cause large changes in θ . These areas correspond to values of θ close to $\pm 90^\circ$ (and $\sin \theta$ close to ± 1) where $\Delta\phi$ measurements show larger errors (the direction of the signal is almost parallel to the base).

of a sophisticated ambiguity resolution algorithm that allowed to measure angles with excellent accuracy ($< 1^\circ$ rms) over the whole band, using various antenna typologies, with tests at TRL6 on real drones, up to the distance of 1 km.

POTENTIAL TECHNOLOGY APPLICATIONS AND EXPLOITATION

The project has allowed the development of a new product, which enriches the Tekne SpA offer, a compact interferometric radio direction finder, easily integrated with the reactive radio-jammer systems in service, to which a cognitive component is thus added in terms of spatial discrimination capacity and spectral identification of broadband signals. This capability is essential in ongoing developments regarding the multi-domain Cyber and Electromagnetic Activities (CEMA) (i.e. a set of cyber and electromagnetic protection measures to safeguard units, systems and connections between them and achieve cyber and electromagnetic spectrum management superiority).

CONCLUSIONS

The RADIC-5G project allowed to develop and test at TRL6 a reactive jammer with direction finding and wideband signals analysis capabilities

(Figure 5 and Figure 6), based on SDR technology, with various innovations:

- Possibility of using an ESA antenna with very fast switching time (one complete revolution per second), even in power (up to 100 W).
- Development of a pure interferometric system, it does not use correlation tables (phase difference values that must be measured a priori for all angles and all frequencies of use). A calibration is done in frequency, but not in angle. The measurement accuracy, thanks to a sophisticated ambiguity resolution algorithm, has proven to be superior.
- The system performs the analysis and classification of the signals, measuring their S/N ratio and the occupied band, and measures the angle for all the signals simultaneously present in the instantaneous band.
- The extremely compact system uses a single antenna system for the 400 MHz to 6 GHz band, and not the classic layout of 3 rings of 5 antennas for the low, medium and high bands.

The algorithms were validated inside anechoic chamber, and then outside in the field, using different types of signal generators and transmission systems (including drones) in realistic environments. The DoA accuracy obtained is better than

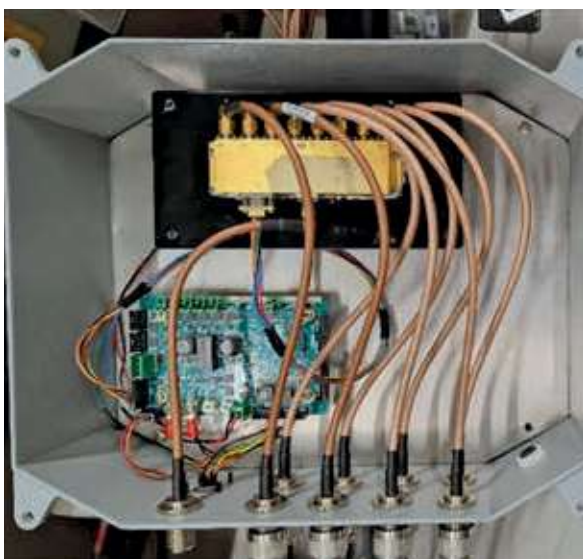


Figure 5 - ESA antenna Control Electronics. The Control Board and the 8-port switch (high power) are visible.



Figure 6 - The interferometric system (5 antenna version). The developed system can be configured with any number of antennas, however arranged.

1° rms for interferometric system, and better than 30° rms for ESA. Future developments concern engineering at TRL7, and in particular the speeding up of the system (porting of the software to

ARM internal to the board and parts of the processing in FPGA), as well as the optimal integration of the DF antennas with the radio jamming component, and in the structure of the vehicle.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

apFFT	<i>All phases Fast Fourier Transform</i>
ARM	<i>Advanced RISC Machine</i>
DF	<i>Detection Finding</i>
DoA	<i>Direction of Arrival</i>
EA	<i>Electronic Attack</i>
ES	<i>Electronic Support</i>
ESA	<i>Electronically Steered Antenna</i>
FPGA	<i>Field Programmable Gate Array</i>
LTE	<i>Long Term Evolution</i>
MIMO	<i>Multiple Input Multiple Output</i>
RISC	<i>Reduced Instruction Set Computer</i>
SDR	<i>Software Defined Radio</i>
TRL	<i>Technology Readiness Level (Livello di maturità tecnologica)</i>
UAS	<i>Unattended Aerial System</i>
UCA	<i>Uniform Circular Array</i>
WiFi	<i>Wireless Fidelity (rete wireless)</i>

KEYWORDS

Reactive Jammer, Cognitive Jammer, Direction Finding, Interferometry, SDR, Cyber, UAS.

PROJECT INFORMATION

PNRM number:	a2018.001
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In the context of STORM project (STORM - Sensors on Mobile and Remote Terahertz Systems PNRM a2017.153) a drone-based THz detector for the detection of air pollutants capable of real-time remote measurements has been developed. The system combines a drone (unmanned aerial system, UAS) and THz-CW laser technology, enabling flexible and high-resolution remote spectroscopic measurements at the point of interest. Furthermore, the data analysis procedure and the dedicated software developed within the project enable the identification and quantification of the target substances. The results obtained show that the combined system has a high stability and is not affected by the vibrations of the UAS in flight despite the altitude from the ground, allowing the detection of multiple substances. The presented test system demonstrates that it is possible to use the combined UAS-THz-CW system for the detection of air pollutants in the atmosphere.

INTRODUCTION

THz spectroscopy (0.1-10 THz) exploits low photon energies (4.2 meV at 1 THz) that do not cause molecular ionization or combustion, making it safe in crowded environments and for biological subjects. This technology allows the non-invasive analysis of atmospheric gases, since many molecules show specific rotational absorption lines in the THz range. Furthermore, the wavelengths involved reduce interference due to particulate scattering.

In this work, we present a compact and portable sensor based on continuous wave laser technology (THz-CW) for environmental monitoring. The device integrates a dedicated database and an identification and quantification algorithm, allowing remote and real-time detection of air pollutants.

The prototype realized within the STORM project is compact and portable and represents an innovative solution for gas detection even when physical obstacles or geographical position can limit the analysis of pollutants deriving from human activities. This combined technology (THz-CW-UAS) opens new perspectives for pollution control and environmental conservation, and contributes to preventive methods for human safety.

TECHNICAL BACKGROUND

Accurate monitoring of air pollutants is essential to assess air quality and mitigate the environmental impact of human activities. However, currently available techniques have several limitations. Conventional methods, such as infrared spectroscopy and sampling-based techniques, often require bulky instruments, laboratory analysis and slow response times. Furthermore, the detection of specific gases in complex environments can be hampered by scattering phenomena and/or spectral interferences.

To overcome these limitations, we propose a solution based on THz continuous wave (THz-CW) spectroscopy, which offers high selectivity and sensitivity in the recognition of volatile organic compounds (VOCs). THz frequencies allow to accurately identify target gases thanks to their characteristic rotational absorption lines, reducing the influence of atmospheric particulate matter.

To address this challenge, we developed a compact and autonomous prototype based on THz-CW laser technology, equipped with a dedicated database and an advanced algorithm for

gas quantification. The system allows monitoring and remote control in situ, improving the efficiency and practicality of measurements. Furthermore, it is designed to be further miniaturized, for example with the adoption of a multi-pass cell, making it an innovative technological solution applicable in critical contexts for environmental monitoring.

METHODOLOGY

The system was designed by combining THz-CW laser technology with a drone (quadcopter) with an autonomy of about 31 minutes (maximum load = 15.06 kg) and features an anti-vibration mechanism to reduce disturbances to the instrumentation (Figure 1). The THz radiation, generated by the heterodyne down-conversion of two infrared lasers, has a high resolution (≈ 10 MHz) in the range between 0.1

and 1.1 THz. The system (Figure 2), based on optical fibers, includes a transmitter and a receiver housed in two 3D nosecones, each containing mirrors for the radiation collimation. The carbon fiber sampling cell is equipped with windows transparent to THz radiation and connected to a pump that aspirates the gaseous substances through a 5 m tube.

An omnidirectional antenna controls the on-board instrumentation and transmits real-time data to the ground station. The gaseous pollutant database, developed in the laboratory, supported the aspiration measurements of single compounds and their mixtures. All measurements are performed with a spectral resolution of 100 MHz and an integration time of 10 ms per point. This allows to record the spectra in a short time without compromising the high resolution of the data.

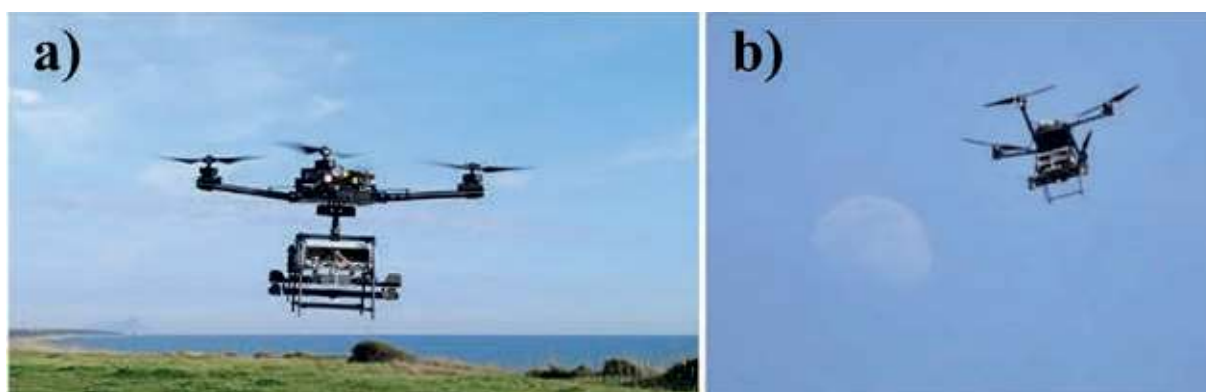


Figure 1 - The assembled UAS-THz-CW system in flight during in-field trials at a) 5 meters and b) 100 meters from the soil level.

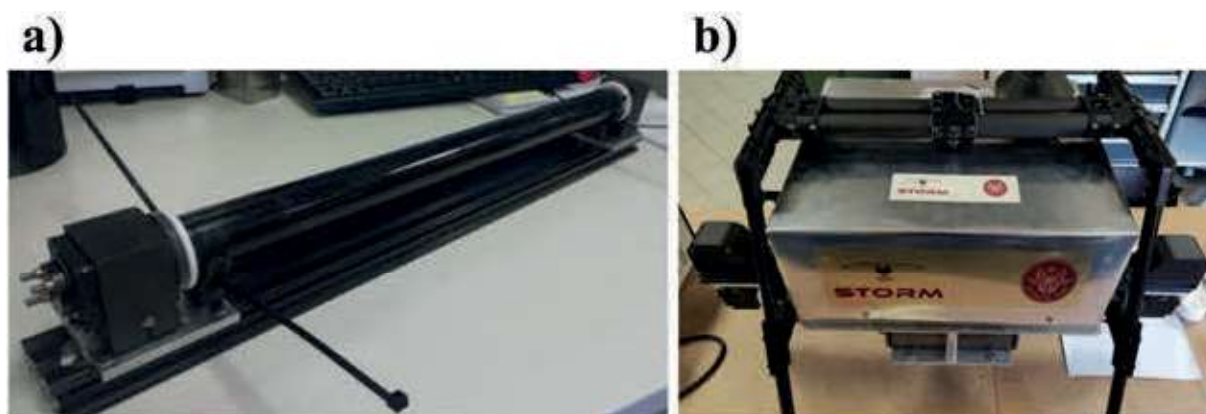


Figure 2 - System assembly: a) sampling cell; b) sampling cell and THz-CW system.

The collected data are processed with a dedicated algorithm based on the Hilbert transform method. The mixture of polluting VOCs containing acetone, methanol and dichloromethane (20%, 40% and 40% in volume, respectively) was aspirated inside the sampling cell of the in-flight prototype. Starting from the database of THz spectra of the individual pure substances, the acquired signals were processed according to the multiple absorbers approach for non-interacting substances: the spectrum of the mixture is reconstructed from a weighted linear combination of pure spectra (Figure 3) and the coefficients allow to recover the quantity of each compound present in the mixture (Table 1).

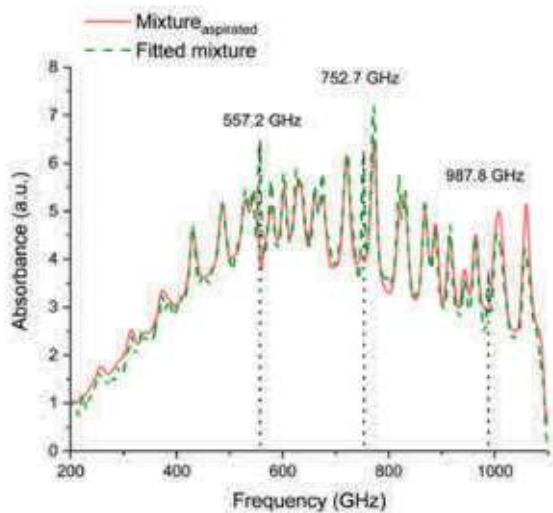


Figure 3 - Comparison between the experimental mixture constituted by acetone, methanol, and dichloromethane (20, 40, and 40% in volume) aspirated inside the sampling cell and remotely investigated by the THz-on-drone system at a flight altitude from the soil level of 5 m and the spectrum obtained from the retrieved coefficients in the range 0.2-1.1 THz. The peaks indicated are linked to water vapour absorptions (557.2, 752.3 and 987.9 GHz).

	Sample volume [%]	Retrieved coefficient [%]
Acetone	20	27
Methanol	40	38
Dichloromethane	40	35

Table 1 - Percentages in volume of the prepared sample and retrieved volume obtained from the fit performed as a weighted linear combination of the pure compounds for the multi-component mixture.

POTENTIAL TECHNOLOGY APPLICATIONS AND EXPLOITATION

The developed system is able to identify and quantify gaseous compounds during the flight phase of the drone using the THz-CW fiber spectroscopy system. This configuration allows to identify sources of gaseous emissions, such as those coming from the subsoil, which could represent a risk to the environment and to human safety. The innovative technology proposed allows to monitor in real time the presence of harmful or polluting gases, providing an important tool for air analysis and for the prevention of potential dangers. In addition to the identification of natural sources of gaseous emissions, the system can be used to monitor anthropogenic emissions, deriving for example from industrial activities, combustion plants, chemical processes or landfills for example.

To this end, the expansion of the database containing THz spectral fingerprints of other potentially harmful compounds will allow to increase the number of detectable taggants, optimizing the accuracy in the identification and traceability of substances.

Thanks to the possibility of operating in mobility through the use of drones, the system offers a non-invasive, rapid and effective detection method, useful for environmental control and the protection of public health. The integration of THz-CW spectroscopy into environmental monitoring systems represents a significant step forward in the early identification of pollution sources and in the sustainable management of atmospheric resources.

CONCLUSIONS

The system developed for remote sensing of polluting gases via THz-CW spectroscopy integrated on a drone is portable and lightweight and it allows high-resolution measurements. During measurements at an altitude of 100 meters above ground, the system detected acetone, methanol

and, for the first time in literature, dichloromethane with this technology.

The results show a high stability of the system, with measurements consistent with laboratory ones thus not influenced by the vibrations of the drone. In addition, a pump connected to a 5-meter tube allows remotely controlled point sampling,

collecting the gas in the sampling cell. The method allowed the identification and quantification of the pollutants in the mixture.

The results demonstrated that the integration of CW laser spectroscopy and drone allows real-time monitoring of air pollutants, with applications in environmental surveillance and industrial emissions control.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

THz	<i>Terahertz</i>
CW	<i>Continuous Wave</i>
UAS	<i>Unmanned Aerial System</i>
VOCs	<i>Volatile organic compounds</i>
meV	<i>millielectronvolt</i>

KEYWORDS

Terahertz; Drone; Remote sensing; Environmental pollution; Gas sensing.

PROJECT INFORMATION

PNRM number:	a2017.153
Organization:	Direzione Armamenti Terrestri
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The PACMAN project (Proficient Artificial intelligence Counter Mine AutoNomous vehicles) aims to develop a system of autonomous vehicles for mine clearance operations, using advanced automatic target recognition (ATR) techniques based on artificial intelligence. The system includes autonomous underwater vehicles (AUVs) and autonomous surface vehicles (ASVs) that cooperate to improve the efficiency and safety of operations. During phase 1, ATR algorithms, autonomous coverage, and multi-vehicle cooperation were developed and tested, with promising results.

INTRODUCTION

The PACMAN project is part of Mine CounterMeasures (MCM) operations, where the use of autonomous vehicles equipped with automatic target recognition (ATR) systems is essential to improve the efficiency and safety of operations. The project aims to develop a modular and reconfigurable system of autonomous vehicles capable of performing clearance operations autonomously and in real-time.

TECHNICAL BACKGROUND

The PACMAN project addresses the problem of mine clearance in maritime contexts, where the use of autonomous vehicles can significantly improve the efficiency and safety of operations. Currently, Mine CounterMeasures (MCM) operations require intensive post-mission analysis, with highly qualified teams of operators examining large volumes of data collected by unmanned vehicles. This process is long and laborious and poses risks to the personnel involved.

Current Mine CounterMeasures (MCM) operations involve lengthy and costly Post-Mission Analysis (PMA) activities, requiring manual analysis of large volumes of data by highly specialized operators and exposing personnel to potential risks. The PACMAN project proposes a system based on small, easily deployable autonomous underwater vehicles (AUVs) that, thanks to automatic object recognition (ATR)

technology and precise navigation, provide a detailed real-time map of potential targets. This approach acts as a force multiplier, reduces the risk to operators, and significantly improves the efficiency of mine clearance operations.

The technological solutions proposed by the PACMAN project include:

- **ATR Architecture:** Development of ATR methodologies based on convolutional neural networks (CNN), which represent the state of the art in this field of artificial intelligence. These solutions allow AUVs to analyze images acquired by payload sensors, such as Forward-Looking Sonar (FLS) and Side Scan Sonar (SSS), in real-time. ATR algorithms are designed to recognize and locate mines and similar objects, significantly reducing the amount of data to be examined.
- **Autonomous Vehicles:** Design and construction of compact, modular, and reconfigurable AUVs equipped with advanced sensors for navigation and data collection. These vehicles can perform clearance missions autonomously, using precise navigation techniques and autonomous coverage path planning (CPP) algorithms.
- **Multi-Vehicle Cooperation:** Implementation of a cooperation system between AUVs and Autonomous Surface Vehicles (ASVs), which act as communication gateways between the underwater and radio frequency domains. This

system improves AUV localization and transmits relevant data to operators in real-time. In Figure 1, the X300 vehicle is depicted equipped with the dedicated payloads for the purposes of this project, while Figure 2 illustrates the typical scenario of multi-vehicle cooperation.

- **Command and Control:** Development and prototyping of a Situational Awareness system for mission management. This application, designed as a user-friendly interface,

allows operators to plan, manage, and monitor the activities of the involved autonomous vehicles easily and intuitively, as well as visualize real-time synthetic outputs generated by the ATR system.

In Figure 3, we see some of the possible visualizations.

These technological solutions aim to improve the efficiency, safety, and speed of mine clearance operations, reducing the risk to personnel and optimizing the use of available resources.



Figure 1 - Render of the autonomous vehicle X300 designed for the PNRM PACMAN. Specifically, the sensors equipped on the vehicle for the detection, classification, and recognition of potential underwater threats are highlighted.



Figure 2 - Representation of the vignette illustrating multi-vehicle cooperation, highlighting the interaction between an underwater autonomous vehicle, a surface vehicle, and the support naval unit.

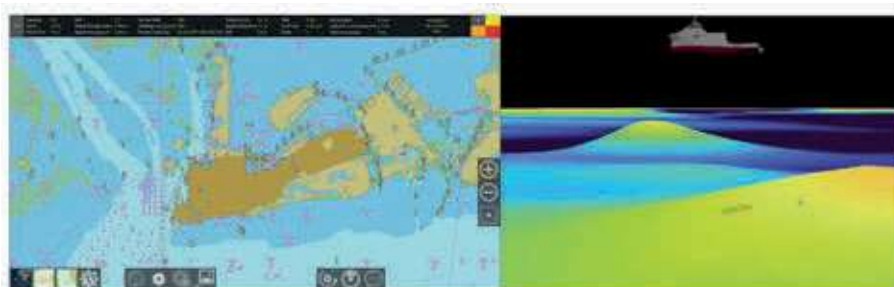


Figure 3 - Command and Control System for Mission Planning and Management.

METHODOLOGY

Phase 1: Feasibility Study and Algorithm Development

During the first phase, feasibility studies were conducted to evaluate the state of the art and identify the most promising technological solutions. This phase included the following activities:

- o **State of the Art Analysis:** Review of existing technologies in the field of automatic target recognition (ATR) and autonomous coverage, with particular attention to convolutional neural networks (CNN).
- o **ATR Algorithm Development:** Implementation and testing of ATR algorithms using acoustic images obtained from Forward-Looking Sonar (FLS) and Side Scan Sonar (SSS) sensors. Various neural network architectures were compared to identify those that represent the best compromise between performance optimization and reduction of required computational power.
- o **Test Platform Design and Construction:** Construction of prototypes of autonomous vehicles (AUVs and ASVs) equipped with advanced sensors for navigation and data collection. These prototypes were used to test the developed algorithms under controlled conditions.
- o **Autonomous Coverage Algorithm Development:** Implementation and testing of a Cover-

age Path Planning (CPP) algorithm to optimize the coverage of target areas, considering the characteristics of the sensors and the operational constraints of the autonomous vehicles.

Phase 2: System Integration and Operational Testing

The second phase of the project involves integrating the hardware and software components developed in phase 1 and validating them through operational tests at sea. The main activities include:

- o **Hardware and Software Integration:** Assembly of complete systems, combining autonomous vehicle prototypes with ATR and autonomous coverage algorithms. This activity ensures that all components work synergistically.
- o **Sea Testing and Validation:** Conducting operational tests in real environments to evaluate the performance of integrated systems. These tests allow verifying the effectiveness of the proposed solutions and identifying any areas for improvement.

The adopted methodology ensures a rigorous and systematic approach to developing PACMAN technologies, ensuring that each project phase is supported by well-defined and targeted research and development activities. In Figure 4, some of the results obtained from the first sea tests can be seen.

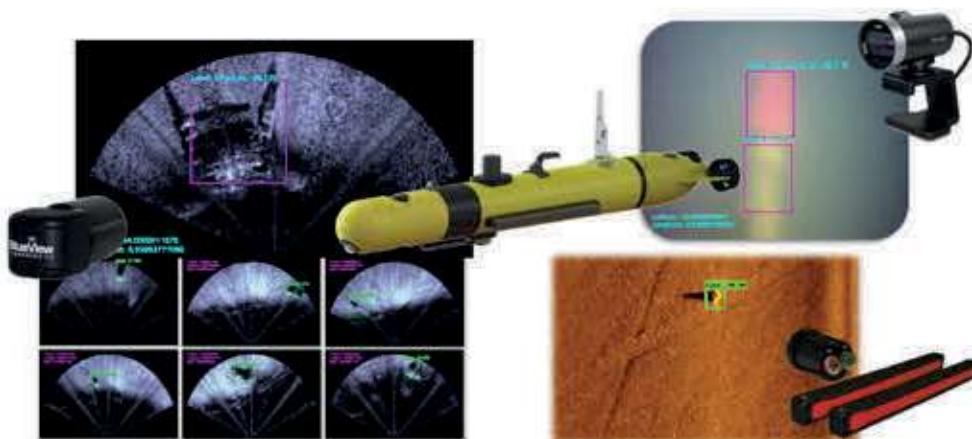


Figure 4 - Data collected during sea tests with various sensors and the operation of different ATR algorithms.

Results

During phase 1 of the project, the following results were achieved:

- **Test Platforms X300 and MGB 300 – ASV:** The necessary platforms for the PACMAN project operational context were built, including an X300 vehicle equipped with a mission module and an MGB300 gateway buoy.
- **Mission Sensor Module Design:** The mechanical design and integration of components within the PACMAN mission module were carried out.
- **Mission Sensor Selection and Procurement:** The necessary sensors for the mission in the PACMAN operational context (onboard computer, navigation sensors, perceptual sensors, etc.) were selected and purchased.
- **Automatic Target Recognition (ATR) Algorithm Development:** State-of-the-art methodologies were tested to perform instance segmentation with FLS and SSS images; a detailed quantitative analysis of the obtained results is proposed.
- **Autonomous Coverage (AC) Algorithm Development:** A CPP algorithm specifically developed to optimally cover a selected area with an FLS-equipped AUV was proposed and tested in simulation.
- **ASV-AUV Cooperation Algorithm Development:** The software architecture for ASV-AUV cooperation was developed, along with the acoustic communication protocol; the results obtained from simulation tests are reported.

POTENTIAL TECHNOLOGY APPLICATIONS AND EXPLOITATION

The technologies developed in the PACMAN project have potential applications in both military and civilian fields. In the military field, the system can be used for mine clearance operations, underwater surveillance, and search and rescue (SAR) in complex or dangerous scenarios. In the civilian field, ATR and autonomous coverage technologies

can be applied to environmental monitoring, underwater archaeological research, and underwater infrastructure inspection.

- **Environmental Monitoring:** Autonomous vehicles can continuously monitor water quality, detect pollutants, identify objects of environmental interest, and assess the health of marine ecosystems, facilitating timely and targeted interventions.
- **Underwater Archaeological Research:** Advanced automatic recognition systems enable the identification, mapping, and continuous monitoring of submerged archaeological sites, facilitating the discovery and preservation of historical and cultural artifacts.
- **Underwater Infrastructure Inspection:** Autonomous vehicles can conduct detailed inspections of critical infrastructures such as pipelines, gas pipelines, submarine cables, and offshore platforms, promptly identifying damage, anomalies, or failures to improve preventive maintenance and reduce operational costs.
- **Port Surveillance and Security:** PACMAN systems can monitor port areas, detecting threats and protecting critical infrastructures, with autonomous operations and real-time data transmission for rapid responses.

CONCLUSIONS

The PACMAN project has demonstrated the feasibility and effectiveness of the proposed technological solutions to improve mine clearance operations through the use of autonomous vehicles. During phase 1, advanced automatic target recognition (ATR), autonomous coverage, and multi-vehicle cooperation algorithms were developed and tested, with promising results. The X300 and MGB 300 – ASV test platforms were successfully built, and the mission sensor was selected and integrated. ATR algorithms based on convolutional neural networks showed high performance in segmenting FLS

and SSS images. The autonomous coverage algorithm demonstrated the ability to optimally cover a selected area, while the ASV-AUV cooperation software architecture ensured effective communication and precise navigation. The developed technologies have potential applications in both military and civilian fields,

improving the safety, efficiency, and sustainability of underwater operations. The next phase of the project involves integrating the systems and validating them through operational tests at sea, with the aim of consolidating the obtained results and exploring further applications of the developed technologies.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

AC	<i>Autonomus Coverage</i>
ASV	<i>Autonomus Surface Vehicle</i>
ATR	<i>Automatic Target Recognition</i>
AUV	<i>Autonomus Underwater Vehicle</i>
FLS	<i>Foward Looking Sonar</i>
MCM	<i>Mine Counter Misure</i>
SSS	<i>Side Scan Sonar</i>
PMA	<i>Post Mission Analysis</i>

KEYWORDS

ATR, AUV, MCM

PROJECT INFORMATION

PNRM number:	a2021.093
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The propulsion of recently built autonomous underwater vehicles (AUV) or semi-autonomous underwater vehicles (ROV) is usually electric and transmitted through propellers, water-jets or pump-jets, which generate hydrodynamic noise, especially at high speeds, making the vehicle easily detectable. The research in question aims to optimize the characteristics of the vehicle, both from the point of view of the hydrodynamic resistance of the vehicle and the generated noise, by designing and building a prototype of a bio-inspired fish-like autonomous vehicle. The program, developed by the CNR-INM and the University of Rome La Sapienza, which has reached the end of phase 2, has permitted, downstream of the detailed design, the creation of a wire-guided (the final product will be completely autonomous) prototype model for the evaluation of the propulsive capabilities of the main propulsive fin. It has also allowed the definition of the functional tests to evaluate the construction and assembly of the prototype, the movement capacity of the actuation components, the acquisition of sensory data and general integration. The entire program represents a challenge in terms of choice of materials, creation of a compact, silent prototype equipped with innovative hydrodynamics and propulsion.

INTRODUCTION

The control of the underwater dimension represents a pressing challenge that has driven technological research in recent years with multiple purposes of both a military nature (data collection, contribution to situation awareness, monitoring and protection of critical underwater infrastructures) and civil (data acquisition, ecosystem protection). In this context, we have witnessed the proliferation of autonomous and semi-autonomous underwater systems of different types and sizes whose technological contents are mainly aimed at ever greater autonomy and discretion. The search for greater autonomy is based on the development of increasingly efficient energy storage systems (lithium ion batteries, fuel cells) and on the containment of the vehicle's consumption through increasingly sophisticated technical and design measures. Discretion is sought mainly through the use of silent propulsion systems but also through the use of camouflage coatings, amagnetic materi-

als and in general low signature be it optical, acoustic, magnetic, etc.

TECHNICAL BACKGROUND

The search for technological solutions aimed at minimizing the consumption of the vehicle and increasing its discretion also involves the study of bio-mimetic propulsion shapes and methods. In particular, locomotion through the use of a caudal fin that effectively simulates the movements of a fish poses technological challenges of particular interest because it involves studies on the materials to be used and on the most effective frequencies both from a propulsive point of view and in terms of silence of the system as a whole. The expected final result is therefore the development of a robotic fish characterized by the ability to move silently and efficiently, for autonomous exploration and data collection and the project focuses on the development and development of the hydrodynamic propulsion structure through the study of a bio-mimetic tail, the robotic structure and the

implementation of guidance algorithms related to the movement of the bio-mimetic underwater vehicle. Energy storage is guaranteed through the use of lithium ion batteries.

METHODOLOGY

The final objective of the project is the creation of an operational prototype in a controlled environment capable of demonstrating the reliability, effectiveness and efficiency of a bio-mimetic platform for the aforementioned underwater activities. The prototype thus conceived and created will serve to provide design and engineered construction indications for operational systems in real scenarios.

Phase 1 of the project had as its object, through the study of possible mission profiles and the state of the art, the definition of the functional and basic design requirements which are summarised below:

- length: 1.5 - 2.0 [m]
- estimated weight: 25 [Kg]
- speed: 0.5 - 1.5 [m/s]
- maximum mission range: 1000 [m]
- morphology: semi/full fish-like

During phase 2, detailed design was carried out with the aim of having, at the end of the phase itself, an prototype, operational in a controlled environment, capable of demonstrating the reliability, effectiveness and efficiency of a bio-mimetic platform for the aforementioned underwater activities. The detailed design led to the identification of the system components starting from the frame elements that make up the load-bearing structure of the prototype, with the related support and locking appendages of the different modules and devices to be housed inside the body of the vehicle. The electric motors for the actuation of the moving parts were then identified, specifically, the main propulsion fin, the stabilizing fins and the swim bladders for regulating the immersion depth. A similar selection was made for the sensor devices necessary for the navigation of the vehicle and data collection in the operational environment. Finally, the functional scheme of the differ-

ent software components of the management and control architecture of the vehicle was designed, through which the autonomous use functions are implemented. Furthermore, a specific experimental setup was designed and built to evaluate the propulsive capabilities of the caudal fin in order to optimize the geometric-operational choices, also including the experimentation of different materials for the terminal part of the fin, in order to evaluate the one with the best performance (Figure 1).

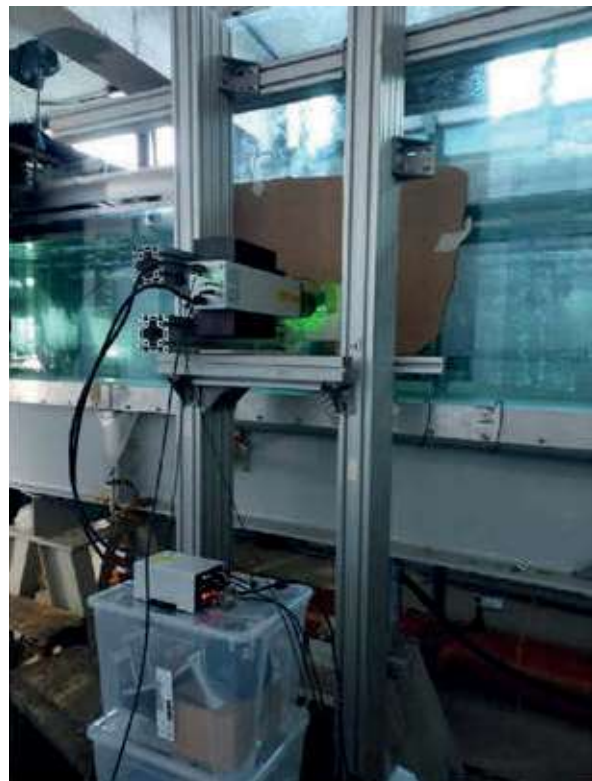


Figure 1 - Experimental setup for the evaluation of the propulsion performances of the caudal fin.



Figure 2 - Frame captured by quick camera during the flexible fin evaluation tests.

The next phase involved the construction of the PERSICO prototype. In particular, the finalization of the technical construction and assembly drawings of the parts consisting of: the framework and the support and locking appendages, the actuation system housings, related mechanical reducers and motion transmission kinematics for the movement of the joints, sealed containers and related accessory components for the assembly of all the functional modules.

The final work package of Phase 2 concerned the preliminary experimentation focused on the definition and execution of preliminary tests for the individual components of the system: sensors, actuation systems, software modules and control ar-

chitecture as well as the general verification tests in the prototype tank.

POTENTIAL TECHNOLOGY APPLICATIONS AND EXPLOITATION

The standard mission target for the PERSICO prototype could be exploration/discovery/data collection activities in the area of interest. Two operating modes are foreseen:

- civil - environmental data collection; the sensor of interest for such data could be a CTD (Conductivity, Temperature, Depth) device for the characterization of salinity and temperature in the water column. In this mode, the support of active acoustic instrumentation could be envisaged (with

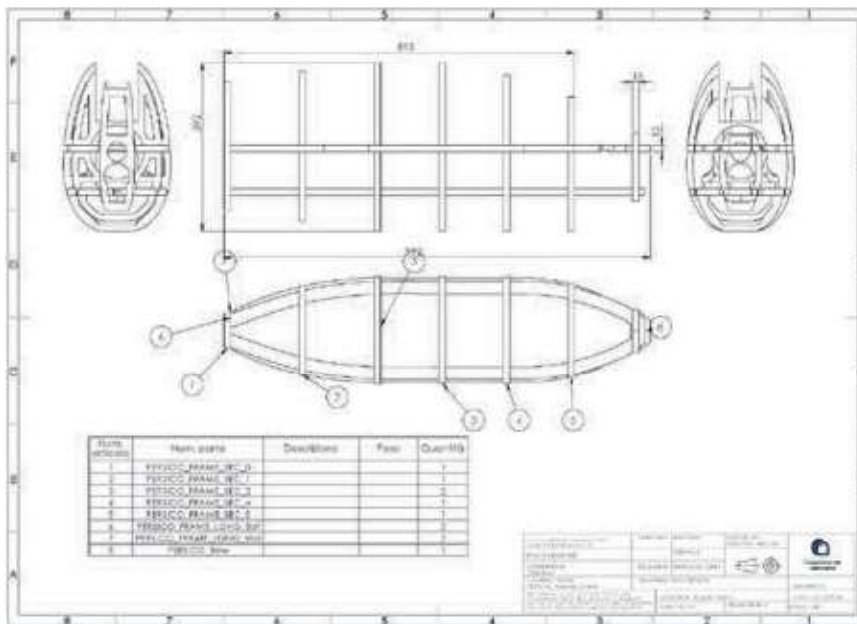


Figure 3 - Technical Drawing of the inner structure.



Figure 4 - The PERSICO prototype during the assembly phase.



Figure 5 - The PERSICO prototype during the sailing tests at CNR-INM in Rome.

consequent introduction of acoustic noise into the operating area) for the real-time localization of the robot during the mission and the possible communication of operating parameters (robot operating status, updating of points of interest, alarms).

- military - exploration and discovery in the area of interest; a hydrophone will be used for the detection of unknown assets and the characterization of the related acoustic profiles. In this mode, the operation of the robotic system could be completely autonomous, therefore there will be no localization/communication between the operator station and the robot.

CONCLUSIONS

The PERSICO program has arrived, since the completion of the second of the three planned

phases, at the construction and sailing testing of a prototype of a robotic fish characterized by significant dimensions that allows a fair amount of flexibility in terms of payload and by an innovative and technologically advanced propulsion system. The sizing of the vehicle itself represents an optimal compromise between the needs of silence and discretion and those of autonomy and load capacity. During the subsequent development, for which the activation of phase three is certainly considered appropriate, further refinements and improvements may be obtained both in terms of effectiveness of the external treatment, for example through a neoprene coating that enhances its camouflage characteristics, and in the development of the autonomous guidance and mission execution system.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

ROV	<i>Remotely Operated Vehicle</i>
AUV	<i>Autonomous Underwater Vehicle</i>
CNR-INM	<i>Consiglio Nazionale delle Ricerche – Istituto di Ingegneria del Mare</i>

KEYWORDS

Drone, Underwater, Fish, Robotic, Bio-mimetic, AUV, ROV.

PROJECT INFORMATION

PNRM number:	a2019.034
Organization:	Naval Armaments Directorate
Responsible entity:	Consiglio Nazionale delle Ricerche – Istituto di Ingegneria del Mare - Università degli Studi di Roma La Sapienza
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The SAFE project aims to study the automatic ability to verify the integrity and security of firmware used in automation systems, regardless of the availability of the corresponding source code. This is because the development and updating of firmware is becoming an increasingly critical element in the lifecycle management processes of Information Technology (IT) and Operational Technology (OT) devices.

In the first two of the three phases of the project, a prototype platform for firmware analysis was developed by applying recurrent neural networks with self-attention (self-attentive RNNs), capable of recognizing similarities between binary files and between functions in assembly language. The research activity generated a set of project technical documentation, which summarizes the state of the art in the use of neural networks applied to the analysis of binary files, as well as use cases for securing (cybersecurity) supply chains. The software prototype developed is capable of identifying malicious code in firmware executables and determining the version of the libraries used for its compilation. This supports in-depth control of the configuration of IT and OT devices in automation systems and assists cybersecurity analysts during platform updates.

INTRODUCTION

The project aims to study and define the best models and most effective algorithms to implement an automatic ability to verify the integrity and security of firmware used in automation systems, both for terrestrial and naval platforms, regardless of the availability of the corresponding source code. Thorough control of the software configuration of information systems and weapon systems is becoming an essential part of the necessary checks to ensure the cybersecurity of the facilities. In fact, the increasing use of Commercial Off The Shelf (COTS) systems in such environments makes supply chain security an extremely critical element. The project specifically involves the use of advanced Machine Learning techniques to directly analyze the binary code in order to identify potential software alterations.

TECHNICAL BACKGROUND

The project's objectives can thus be summa-

rized into two main goals when the source code is unavailable:

- a. Verify the integrity of a firmware installed on an operational system through automated analysis of similarity between functions. This activity allows verification that two different versions of firmware originate from the same source code when it is not available, i.e., determining whether there are different sources for the two firmware versions.
- b. When two firmware do not derive from the same source code, such as two successive versions of the same firmware, understand which functionalities are common and which have been added in the new firmware.

A solution based on neural networks was chosen for practical reasons: once trained, they require fewer computational resources compared to other technologies and offer good perfor-

mance in terms of time. Specifically, the project focuses on using self-attentive recurrent neural networks (Lin et al., 2017), as detailed in the methodology section. Attention mechanisms represent a significant advancement in modern neural networks, allowing focus on the most relevant parts of the input for more effective problem-solving.

Binary analysis is traditionally conducted with static, dynamic, or symbolic execution techniques. Although accurate, these methodologies are resource-intensive in terms of time and resources. An alternative involves expert Reverse Engineers who manually analyze code using support tools. However, their high cost and task complexity limit the number of binaries that can be analyzed within a given period.

State-of-the-art solutions with neural networks rely on graph neural networks and the use of man-

ual features (Xu et al., 2017). In the SAFE project, it was decided not to use manual features because many recent studies show they are sub-optimal compared to automatic features.

METHODOLOGY

The SAFE project has led to the development of a prototype that allows users to analyse embedded system firmware starting from the binary code alone. At the core of the project is a neural network that transforms functions from assembly code into numerical vectors (known as embeddings, with an example shown in Figure 1. Semantic similarity between functions can be calculated using these embedding based on Euclidean distance.

An overview of how this neural network operates is depicted in Figure 2. The assembly code function is first transformed into a sequence of

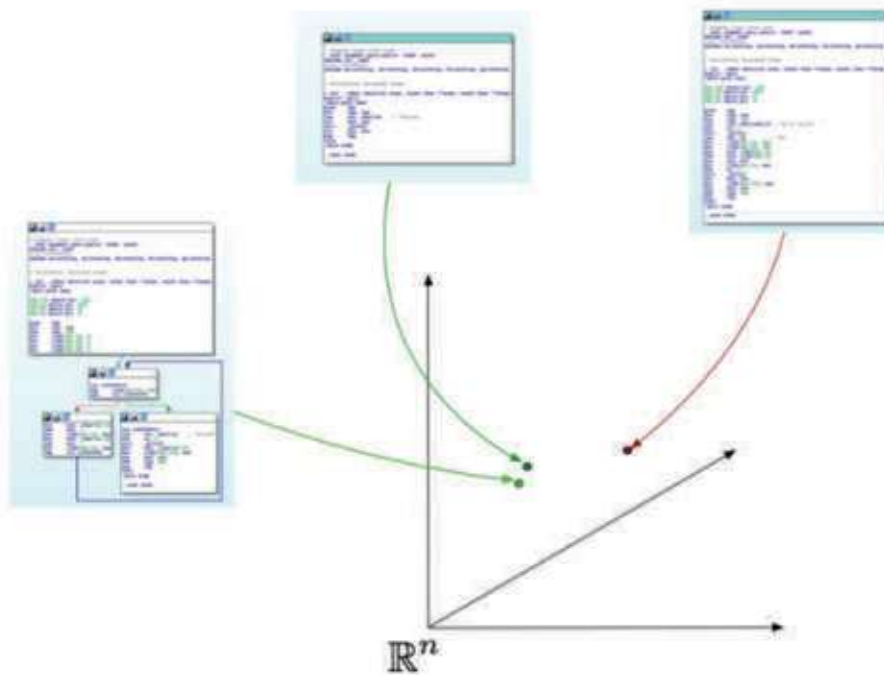


Figure 1 - Example of transforming assembly functions into embedding vectors demonstrates the neural network's ability to capture semantic similarities and differences between functions. In the figure, three different assembly functions are transformed into three distinct vectors. The two similar functions are converted into vectors that are close together (see the green points in the diagram). Meanwhile, the dissimilar function is transformed into an embedding vector that is far from the others (red point).

vectors through a mechanism that converts each assembly instruction into a dense feature vector. The methodology employed is an adaptation of Word2Vec (Mikolov et al., 2013), originally developed for natural language, applied to assembly code. These vectors are then processed by a recurrent neural network with self-attention, a technique previously used in literature for natural language analysis. An innovative aspect of the project was the development of techniques to make assembly code compatible with these solutions through preprocessing strategies aimed at reducing the number of analysable assembly instructions by the network.

The SAFE neural network was trained to generate embeddings using Siamese training. With this technique, two copies of the network are

created and trained on pairs of functions: the networks must produce nearby vectors when the input pair is similar and distant vectors when it is dissimilar. An example of a Siamese network is shown in Figure 3.

The training was carried out on datasets developed within the project's scope, consisting of millions of functions written in assembly code. Some experiments highlighting the performance of the SAFE network are shown in Figure 4.

In the experiments, precision (the number of correct results out of the total) and recall (the number of positive results identified out of the total positives) were measured for the network when used to search for a function within a database of similar items.

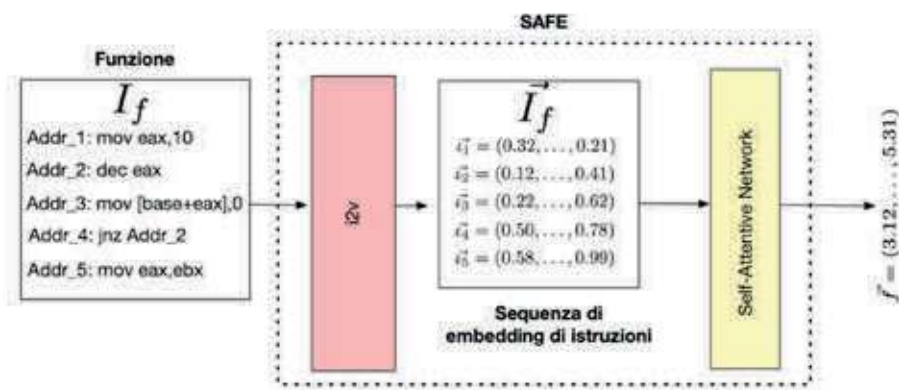


Figure 2 - High-level architecture of the SAFE neural network. The network takes as input a function written in assembly code and transforms it into a numerical vector.

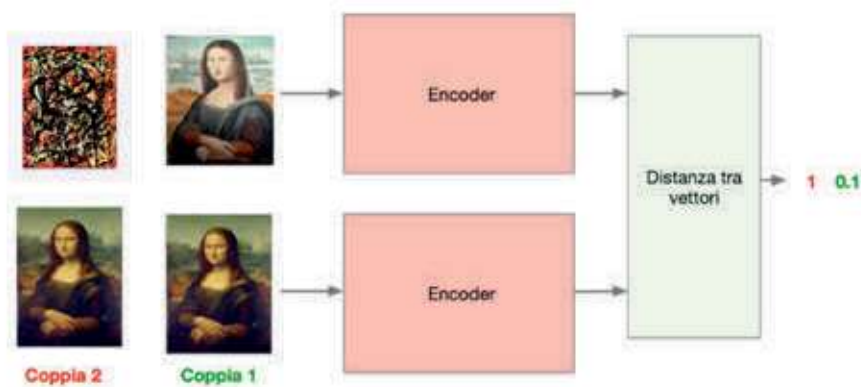


Figure 3 - Example of Siamese training. The network is provided with similar pairs (in the figure, the Mona Lisa and its reproduction) and dissimilar pairs (in the figure, the Mona Lisa and an abstract painting). The networks must produce distant vectors in the case of dissimilarity and nearby vectors in the case of similarity, with distance values indicated by red and green to the right.

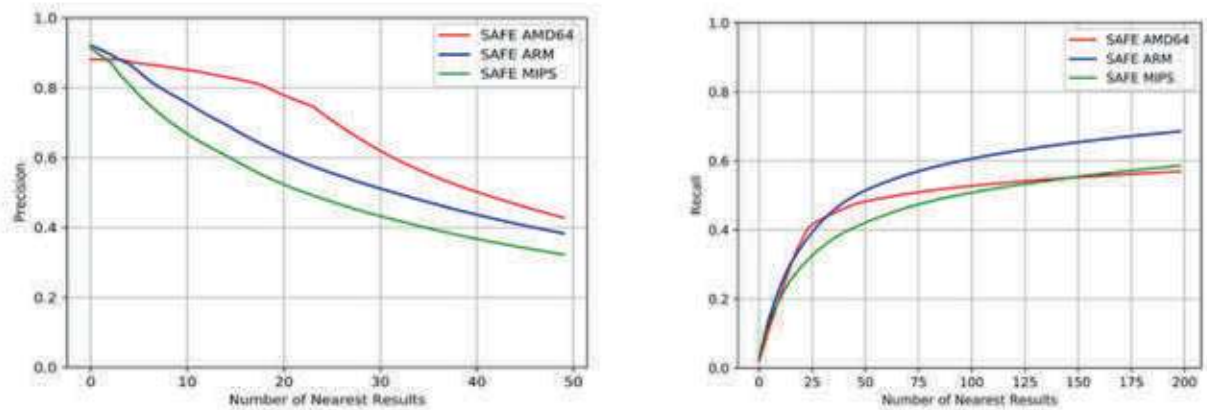


Figure 4 - Results of the SAFE network on test datasets for x86-64, ARM, and MIPS functions.

POTENTIAL TECHNOLOGY APPLICATIONS AND EXPLOITATION

The results obtained in the PNRM SAFE project could have significant practical implications in controlling the potential compromise of the supply chain of embedded systems, even in military contexts.

The use of SAFE as a firmware validation tool would allow the end user to check the firmware's security before updating the device. The SAFE system generates a report after the analysis, which can be used to detect the presence of anomalies, outdated or vulnerable libraries, and potential malware. In the case of detected anomalies, the operator could halt the update process and send the firmware for a more thorough Reverse Engineering inspection.

CONCLUSIONS

L'analisi dei *firmware* tramite la metodologia inThe analysis of firmware using the methodol-

ogy developed by SAFE proves to be an effective method for detecting potential anomalies or the presence of outdated libraries within the firmware itself, without the need to analyze the source code. The system has been shown to be effective on the main hardware architectures used in embedded systems, such as X86, ARM, and MIPS. The use of SAFE has been tested on both civil and military automation systems, yielding promising results in both cases. The diversity of firmware types present in various systems used in military environments represents a significant challenge, which will be addressed in the final phase of the project (Phase 3). The investigation of new analysis techniques, the study of emerging architectures, and the improvement of performance in terms of analysis time and detection accuracy are certainly potential developments for the project.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

SAFE	<i>Self-Attentive Function Embedding for embedded Systems</i>
IT	<i>Information Technology</i>
OT	<i>Operational Technology</i>
RNN	<i>Recurrent Neural Network</i>
COTS	<i>Commercial Off The Shelf</i>

KEYWORDS

Reverse engineering, Firmware integrity, Binary similarity, Neural Network, Supply-chain, Malware analysis, AI, Embedded system.

PROJECT INFORMATION

PNRM number:	a2019.195
Organization:	Directorate of Naval Armament (NAVARM)
Responsible entity:	CY4GATE S.r.l. e Università degli Studi di Roma La Sapienza
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The use of remotely piloted assets is gaining increasing relevance, partly due to the evolution of data transmission technologies and Artificial Intelligence to support operators. Despite the aforementioned developments, a significant number of military activities still remain carried out using traditional assets directly piloted by personnel due to limitations in integrating remote systems with current Command and Control solutions.

The SCIAMANO system aims to study the integration of such unmanned systems with the model of a traditional surface naval unit.

The first phase of the project involved defining the operational, system and maintenance requirements of the SCIAMANO system and its subsystems, leading to the creation of a conceptual design of the drone carrier ship that meets the identified physical and functional constraints.

The work conducted was of fundamental importance in defining the requirements and identifying the challenges and possible solutions related to the integration of drone swarms into naval platforms. In fact, the design of a drone carrier ship represents a test bed to concretely address the engineering problems that arise with respect to more conventional designs. The results obtained enabled the definition of simulation/design models needed to validate optimal solutions.

INTRODUCTION

A large number of maritime military activities are now carried out using conventional surface or submarine assets, piloted with established but limited effectiveness and exposing the crew to associated risks. The use as support of individual remotely piloted assets is today partially integrated due to limitations associated with current Command and Control solutions and Communications architectures. Not the least, increasing importance is being given to the need for coordination of groups of drones so that they act in a combined manner with the autonomous conduct logic of individual elements.

The SCIAMANO system aims, through the management of drone swarms (“swarms”) of surface, underwater and airborne drones, to increase the effectiveness and persistence associated with the execution of military activities, while reducing or eliminating altogether the exposure of personnel to related risks.

Thus, the project aims to challenge the design of a ship by addressing technological and design challenges aimed at being able to integrate the aforementioned drone swarms on board ship units. The technological solutions that define the SCIAMANO system are based on the selection and customization of specific drones, the development of a new C3 (Command, Control and Communication) system, the design of appropriate launch and recovery systems at sea, and the definition of specific logic to perform unmanned and autonomous functions.

TECHNICAL BACKGROUND

The first phase of the study focused on defining the Concept Design of the SCIAMANO drone carrier ship, comprising an evolved C3 system for the operational management of swarms of unmanned vehicles (drones), the associated launch and recovery systems, and all necessary facilities

for embark, disembark, mission preparation and conduct, and maintenance.

SCIAMANO will therefore need to be capable of handling swarms of unmanned aerial, surface (naval and possibly land-based) and underwater vehicles, to be deployed for isolated ship operations and/or embedded in a more complex cooperative environment. The operational scope taken as a reference includes all military activities identified at the NATO level within the MTP-01 standard. These are operations conducted from the sea through the application of various forms of combat; anti-aircraft operations are excluded, but military assistance and dual activities, such as environmental surveys, are included.

Central to the project was the definition of drone swarms coordination logics so that they act in combination with the autonomous conduct logics of individual elements. The management of coordinated aggregations of drones (swarm, or group) was analyzed in both the homogeneous (e.g., all aerial drones) and heterogeneous (e.g., combination of surface, underwater, and aerial drones) case in order to increase the effectiveness and persistence associated with the execution of such activities while minimizing personnel exposure to direct threats and/or risks.

The definition of the SCIAMANO ship was, therefore, driven by the goal of achieving a functional and harmonious integration of drones and their enabling subsystems with the ship architecture, evaluating possible new configurations for future naval units. The project also included the identification of requirements for the SCIAMANO system as a whole and the identification of hardware components, with a particular focus on COTS products, and enabling technologies.

METHODOLOGY

During the first phase of the project the Operational Requirements and their allocation to the subsystems, technologies that enable the realization of the SCIAMANO system, physical and functional requirements along with maintenance and operational requirements, were first identified and defined.

Next, the focus shifted to the enabling elements for the realization of the SCIAMANO ship, identifying a technical solution that implements the hardware elements, through Commercial Off-the-Shelf (COTS) components, adapted or specifically designed components, and the software elements by defining their logic.

Finally, the main characteristics of the SCIAMANO ship dictated by the operational, physical and



Figure 1 - Perspective view of the SCIAMANO ship concept.

functional requirements identified and the solutions enabling the integration of its subsystems were outlined based on the results obtained. In this sense, the draft of a ship was defined to validate the constraints and design choices to be employed through the determination of the main dimensional factors (length, displacement, ...), the top side and the main internal rooms. The focus has been on the enabling elements for the realization of the SCIAMANO ship and in particular on the solutions for the integration of the types of unmanned systems and their launch/recovery equipment, together with the areas and arrangements for their logistic/maintenance support.

Figure 1 shows a perspective view of a hypothetical Ship that meets the aforementioned requirements, while Figure 2 shows one of the solutions identified for the use of underwater drones (so-called moon-pool).

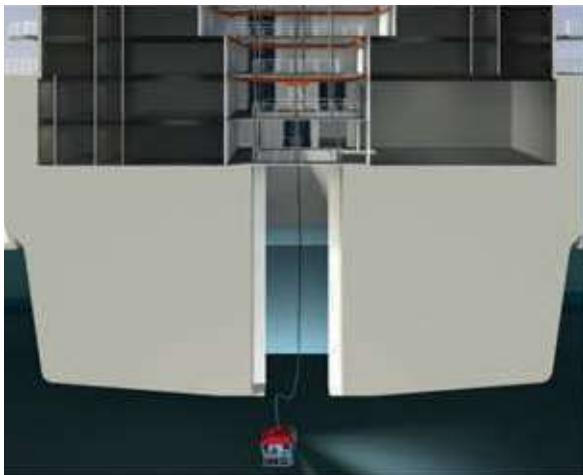


Figure 2 - Solution identified within the SCIAMANO ship concept for the use of underwater drones.

POTENTIAL TECHNOLOGY APPLICATIONS AND EXPLOITATION

The activity conducted in the first phase of the project was of fundamental importance in defining the requirements to be possessed by a naval platform capable of operating drone swarms. It was also possible to focus on the subsystems capable of integrating remote piloting technologies of assets and meeting the operational require-

ments imposed by the deployment scenarios of the Italian Navy units.

The ship and subsystem concept identified does not represent a stand-alone finished product, but provides the basis for subsequent development or integration of remotely piloted systems on newly developed or currently in-line naval units. In this sense, it is possible to elevate the Navy's degree of operability in the below- and above-surface combat domains by organically employing unmanned assets.

CONCLUSIONS

The outcomes achieved at the end of the first phase of the project were very positive as they are akin to the line of technological innovation pursued by the Defense. In current and future geostrategic scenarios, in fact, the deployment of new naval units equipped with various types of airborne, as well as naval and underwater drones, will allow for a range of wide-area intelligence and surveillance missions, along with disruption and saturation actions of adversary defenses through swarms.

In fact, the study of a drone carrier ship represents a concrete area of analysis aimed at tangibly addressing the engineering challenges that arise with respect to more conventional designs. The results obtained with SCIAMANO allowed the definition of simulation and design models necessary to identify and validate optimal solutions.

The persecution of the program will enable the completion of what has already been achieved through the use of a virtual model that will be used for the evaluation of project performance and effectiveness in reference operational scenarios. This will complement traditional system engineering, ship design and operational concept validation methodologies in order to lay the groundwork for the development of a digital twin that can be used to support the design of other next-generation naval units with capabilities similar to SCIAMANO's requirements.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

C3	<i>Command, Control and Communication</i>
COTS	<i>Commercial Off-the-Shelf</i>

KEYWORDS

Drones, *Unmanned*, Drone carrier, C3, *Concept*, *Digital Twin*.

PROJECT INFORMATION

PNRM number:	a2021.047
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The WAVE project (Wearable Assistant for VETERans in sport), carried out in collaboration between the Centro Veterani della Difesa (CVD), Scuola Superiore Sant’Anna (SSSA), the Università degli Studi di Roma “Foro Italico” (FOROIT), and IRCCS Fondazione Don Carlo Gnocchi ONLUS (DONGNOCCHI), aims to improve the quality of life of veteran patients by encouraging sports participation through the development and use of a wearable sensor network equipped with a persuasive interface. To achieve this, advanced and personalized computational methods will be developed and tested for the quantitative assessment of athletic movement. Finally, a persuasive interface will be designed to provide athletes with feedback aimed at optimizing their performance and reducing the risk of injury. The system developed within WAVE—integrating hardware (wearable sensors) and software (advanced data analysis algorithms and a persuasive interface)—ultimately targets both veterans and civilian patients with disabilities engaged in sports, enhancing their quality of life through adaptive athletic training.

INTRODUCTION

The benefits of sports participation for people with disabilities are well-documented, extending beyond physical health to psychological and motivational well-being. Sports promote self-esteem, socialization, and a sense of self-efficacy, while reducing social isolation and the risk of depressive symptoms (Martin Ginis et al., 2016). Research shows that regular physical activity stimulates the release of endorphins and neurotransmitters like serotonin, improving mood and alleviating depressive symptoms (Caspersen et al., 1985). Moreover, sports provide tangible goals and personal challenges, enhancing motivation and a sense of achievement (Shapiro & Martin, 2010). For people with disabilities, these effects are particularly significant, as sports serve as a tool for empowerment, helping them overcome perceived limitations and build a positive identity (Taub et al., 1999). During athletic activity, health monitoring and sensor-derived parameters—such as motion patterns associated with injury risks—can be tracked via a smartphone

or tablet app. This technology could provide users with real-time feedback to avoid hazardous situations, safeguarding their health while optimally stimulating performance improvement. The system would adapt to the athlete’s potential and prioritize injury prevention tailored to their specific sport.

TECHNICAL BACKGROUND

While technological solutions exist for individual assistive devices for disabled athletes - such as prosthetics optimized for specific sports to reduce overuse injury risks, wheelchairs with specialized features like reinforcements or suspension systems, protective suits, or fatigue-monitoring sensors - there are currently no technologies addressing the prevention of incorrect motor gestures that could lead to sport-specific injuries. Additionally, the use of commercial wearable sensors to monitor fatigue in disabled athletes presents several limitations, as these devices are typically designed and calibrated for able-bodied athletes. Multiple studies (Mason et al., 2020; Smith

et al., 2019; Borghese et al., 2018) have demonstrated that physiological and biomechanical parameters in disabled athletes can differ significantly, necessitating personalized data interpretation. The WAVE project aims to overcome these limitations through a wearable sensor network and a custom data analysis algorithm specifically designed for archery and para-rowing athletic practice.

METHODOLOGY

In the initial project phase, we conducted an in-depth study of existing solutions for monitoring athletic movements in disabled athletes, assessing their applicability to the specific context of the WAVE project. This research resulted in the publication titled “Wearable Sensors in Sports for Persons with Disability: A Systematic Review,” which provides a comprehensive overview of wearable sensor applications in sports for disabled people. However, the review revealed that the number of published scientific studies in this field remains extremely limited, and the variability among disabled athletes makes the development of generalized experimental protocols particularly challenging. Following this systematic review, it became clear that one of the project’s key objectives must be the development of flexible and adaptable systems tailored not only to the specific sport discipline but also to the individual athlete’s needs. The literature review concerning disabled athletes did not identify any pre-existing solutions based on wearable sensors that incorporated automatic algorithms for recognizing sports movements or segmenting them into phases. In WAVE, however, automatic classification methods will be applied to identify technical movements that either increase the athlete’s risk of injury or deviate from proper execution. Furthermore, no existing technological solutions specifically targeting disabled athletes were found with the aim

of enhancing adherence to sports practice. The study population was defined through consultations with the Centro Veterani della Difesa, where the number of available veteran military athletes and their respective sports disciplines were evaluated. The selected disciplines were archery and rowing. Following the systematic literature review and a focus group with an identified para-archery coach, a list of parameters requiring measurement/estimation was established for the WAVE project. This list is presented in Table 1.

To quantify (or subsequently estimate) these parameters, it was determined that the measurement protocol should include the following instrumentation: wearable sensors (Magnetic Inertial Measurement Units - IMUs), surface electromyography (EMG), and a stereophotogrammetric system, which serves as the reference system for measuring 3D body segment positioning. Additionally, the use of a chest strap for single-lead electrocardiogram (ECG) measurement was incorporated. The number of IMUs and EMG probes, along with their respective placements on the athlete, are illustrated in Figure 1 and described in detail in Table 2.

Following the same approach used for archery, the experimental protocol for rowing tests – to be conducted with both able-bodied and disabled athletes – was defined based on the literature review and focus groups with two rowing and para-rowing coaches. The protocol includes the following instrumentation: wearable sensors (Magnetic Inertial Measurement Units - IMUs and heart rate monitor), surface electromyography (EMG), and a stereophotogrammetric system. The number of IMUs and EMG probes, along with their respective placements on the athlete, are detailed in Table 3 and Figure 2.

The objective of this activity, concluding Phase 1, was to plan, design and develop pilot feasibility tests involving the disciplines and instruments covered by the project on able-bodied athletes

OVERVIEW			
PARAMETERS	LITERATURE	CRITICALITY	MISURE
Tremor and oscillatori	Markers on the scapula and distal humerus, acceleration components IMU on hand/arm IMU on bow Markers on bow	Not wearable The movement of the bow depends on the Type of Arco (Olympic, Compost) Extra weight	Tremor/oscillation quantification In which phase of the shot? Is it related to the duration of the phase? Is it associated with fatigue?
Postural oscillation	Force plates IMU on the pelvis	Complex pelvis analysis in the athlete in wheelchair. Alternatives: - IMU on the trunk - Sensorized seat	Estimate of the balance Amplitude and direction of oscillations
Times/phases	EMG CAM IMUs on the hands		Duration of the phases Intra-subject variability
Heart rate and respiratory rate	Heart rate monitor	Spirometry, how far the parameters are related to respiratory?	Heart rate and its variability
Muscle activity	EMG	Each athlete develops a personal strategy, according to disability	RMS
Grip force distribution	FSR	It is necessary to sensorize the bow	Grip force
Reaction time to the clicker	Microphone Mechanical switch	Wearable implementation	Reaction time

Table 1 - List of quantities to be monitored during the sport practice of para-archery for the objectives of the WAVE project.

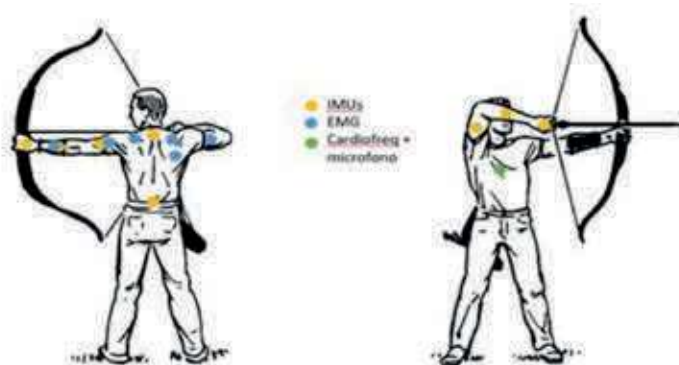


Figure 1 - Provision of the sensor wearable in the practice of the para-archery.

Sensors	N.	Position
IMU (Inertial Measurement Units)	8+1	Hand, forearm, arm (both limbs) Trunk (at the level of the sternum) Pelvis (L4-L5) Head
EMG	8	Arm stretching the rope Biceps, upper trapezius, posterior deltoid (triceps rhomboid) Arm holding the bow: upper trapezius and medial deltoid
Single lead electrocardiography	1	Chest strap
Stereophotogrammetry	39 markers	PLUG IN GATE mode

Table 2 - Description of sensor placement in archery.

Sensors	N.	Position
IMU (Inertial Measurement Units)	9	Hand, forearm, arm (both limbs) Trunk (at the level of the sternum) Pelvis (L4-L5) Head
EMG	8	Both upper limbs Biceps, upper trapezius, posterior deltoid (triceps rhomboid), pectoral
Single lead electrocardiography	1	Chest strap
Stereophotogrammetry	15 markers	Trunk and upper limb

Table 3 - Definition of the quantities to be acquired for the sporting practice of para-rowing.



Figure 2 - Positioning of the sensor wearable for the sports practice of para-rowing.

and analyze the resulting data. The result of this activity allowed the development/implementation of experimental protocols and the acquisition of preliminary data for the implementation of data analysis algorithms and extraction of information relating to the monitoring of the technical gesture, performance optimization and injury risk monitoring. The pilot tests are carried out at the CVD motion capture laboratory.

In the archery discipline, the data analysis focused on identifying the start and end time of each shot and on the different phases of the technical gesture under examination. In particular, four phases were identified (for each type of test):

- Bow raising (or set-up phase): when the bow is raised, the shoulder of the arm holding the arrow (already nocked) performs a flexion

movement, while the elbow begins the supination movement.

- Drawing Phase (or draw phase): the drawing phase is made evident by the abduction movement of the shoulder. The angle goes from a negative value (it starts from a condition of adduction of the shoulder) to a positive one.
- Aiming Phase: At this point all the joint angles are almost constant. The archer is still to evaluate the orientation of the bow and arrow.
- Release and Follow-Through (or simply follow-through phase): As soon as the arrow is released, the shoulder performs a further adduction and external rotation movement. The follow-through phase is determined by constant joint



Figure 3 - Archery - Instrument calibration phase.



Figure 4 - Archery - Stereophotogrammetric acquisition of the sporting gesture.

angles: the archer pauses for a moment before relaxing the position and concluding the shot.

The identification of these phases will be based on specific characteristics of the measured signals, depending on the instrumentation used. The comparison of these characteristics and the evaluation of the accuracy in identifying the phases using wearable sensors only will be the subject of the activities of Phase 2 of the WAVE project.

POTENTIAL TECHNOLOGY APPLICATIONS AND EXPLOITATION

Wearable technology designed specifically for disabled athletes could have numerous uses and applications, both in terms of injury prevention and motivational support. Here are some potential benefits and applications:

a. Injury prevention

- **Real-time biomechanical monitoring:** Integrated sensors could analyze specific movements (e.g. wheelchair pushing, athletic gesture) to identify potentially harmful patterns and suggest corrections, reducing the risk of injuries from overload or incorrect movements.
- **Early warning of fatigue:** Devices could detect signs of muscle fatigue or joint stress, allowing athletes to adjust training intensity and prevent injuries.

- **Personalized protection:** Sensors could activate protection systems (e.g. smart padding) in case of sudden movements or falls, especially in high-impact sports like skiing or wheelchair basketball.

b. Motivational support

- **Instant and personalized feedback:** Providing real-time data on progress, performance, and goals achieved can increase athletes' motivation and self-efficacy.
- **Gamification:** Integrating game elements (e.g. virtual rewards, challenges) based on the data collected can make training more engaging and fun.
- **Connection with coaches and teams:** Wearable technologies could share data with coaches and physical therapists, creating a continuous and personalized support system.

c. Performance optimization

- **Historical data analysis:** Devices could store data on past performances, helping athletes and coaches identify areas for improvement and plan more effective training.
- **Adaptation to specific disabilities:** Technologies calibrated for specific disabilities (e.g. amputations, paraplegia) could provide guidance on how to maximize athletic efficiency without compromising safety.

d. Inclusion and participation

- **Accessibility for all levels:** Easy-to-use devices could be adopted by both professional and amateur athletes, promoting greater participation in sport.
- **Awareness and sensitization:** The use of these technologies could increase the visibility of the needs of disabled athletes, pushing for further innovation and inclusive policies.

e. Social and economic consequences

- **Reduction of healthcare costs:** Preventing injuries means reducing medical and rehabilitation costs, with benefits for athletes and healthcare systems.

- **Promotion of Paralympic sport:** Advanced technologies could attract more investment and sponsorship, contributing to the growth of Paralympic sport.

to materialize by mid-2025, will involve the development of advanced computational methodologies and preliminary implementation of the solution. Specifically, this second project phase will continue developing the advanced computational methodologies (initiated in Phase 1) for extracting performance indicators and risk factors for the selected sports disciplines (archery and rowing). Additionally, the various hardware+software solution components will be integrated by implementing its key functions and conducting initial testing phases.

CONCLUSIONS

The WAVE Project Phase 1 included the analysis of the state of the art, definition of the study target, design of the experimental protocol, identification of sensor systems, and preliminary testing activities, all completed by February 2021. Phase 2, whose contractual commencement is expected

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

CVD	<i>Centro Veterani della Difesa</i>
EMG	<i>Electromyography</i>
IMU o MIMU	<i>Magnetic Inertial Measurement Units</i>
WAVE	<i>Wearable Assistant for VEterans in sport</i>

KEYWORDS

Veteran Sports, Motion Analysis, Performance Evaluation, Sport Biomechanics, Wearable Sensors.

PROJECT INFORMATION

PNRM number:	a2018.101
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In previous PNRM projects (named NIB1 and NIB2), an active compound (Ebselen) was identified as capable of counteracting the effects of botulinum toxin in the animal model. The SPES project (Synthesis, Production, and clinical trial of Ebselen) aims to confirm Ebselen's efficacy in humans in order to develop a drug capable of eliminating or reducing the effects of botulinum toxins. Ebselen, synthesized during the phase 1/2 of the project, was able to protect *in vitro* primary cultures of mouse cerebellar granule cells from the action of botulinum toxin type A, and *in vivo*, it reduced the duration of toxin-induced paralysis and decreased mortality by 50% in mice treated with a lethal dose of the toxins. Furthermore, it was confirmed that the active compound is not toxic at the administered doses. The phase 2/2 of the project will consist of phase 1 clinical trial in humans. It is important to emphasize that if this efficacy is also demonstrated in humans, the armed forces, as well as public health systems, would have access to a treatment for botulism, serving as a medical countermeasure in the event of a bioterrorist attack or an epidemic outbreak.

INTRODUCTION

Botulinum neurotoxins (BoNTs), the most toxic substances known to date, are produced by bacteria of the *Clostridium* genus (*C. argentinense*, *C. botulinum*, *C. baratii*, and *C. butyricum*) [1]. BoNTs represent the etiological agent of botulism, a rare but fatal disease if not treated promptly. Due to their extreme lethality, ease of production, transport, and dissemination, BoNTs are classified by the Centers for Disease Control and Prevention (CDC) in Atlanta as Category A biological agents, indicating their potential for deliberate misuse in bioterrorism or warfare scenarios [2-4]. Currently, no fully effective therapeutic strategies exist to neutralize BoNTs. The only available therapy, in addition to supportive care (e.g. mechanical ventilation), is based on the administration of specific post-exposure antisera. However, antitoxin therapy presents several limitations, as the risk of individual hypersensitivity reactions, long times due to the production of toxin-specific antisera, and high associated costs.

In the context of previous PNRM-funded research projects, a small-molecule compound, Ebselen,

was identified as a promising therapeutic agent capable of counteracting BoNT activity in animal models [5-6]. The aims of the SPES project (Synthesis, Production of Ebselen, and clinical trial of Ebselen) is to synthesize this compound for human use - currently unavailable on the pharmaceutical market - and to initiate the clinical trial.

TECHNICAL BACKGROUND

Botulinum toxins cause a severe neuromuscular disease, botulism, which is characterized by flaccid paralysis. At cholinergic synapses, the toxins cross the plasma membrane of nerve cells and, within the cytoplasm, inactivate one of the proteins of the SNARE complex (SNAP-25, synaptobrevin, or syntaxin), thereby blocking the release of the neurotransmitter acetylcholine (Figure 1) [7-8]. The resulting paralysis can persist for several weeks to months, requiring continuous monitoring of vital functions. Based on their serological properties, eight toxin types are currently recognized (A-H), subdivided into more than 30 subtypes (e.g., A1-8; B1-8; E1-12,

etc.). They share a conserved structure consisting of a heavy chain (100 kDa) and a light chain (50 kDa), linked by a disulfide bond that must be cleaved (reduced) to activate the toxin by releasing the catalytic subunit [9]. To date, there are no therapies aimed to solving the problem. Therefore, it is critical to develop a pharmacological agent capable of eliminating or reducing the effects of botulinum toxin.

By studying the mechanism of action of BoNTs, a therapeutic strategy has been identified to block its activation by acting directly on the cellular enzymatic complex Thioredoxin Reductase-Thioredoxin (TrxR-Trx) [10] through the administration of an inhibitor: Ebselen (2-phenyl-1,2-benzisoselenazol-3(2H-one). This substance has demonstrated the ability to inhibit the action of botulinum neurotoxin both *in vitro* in neuronal cells and *in vivo* in animal models.

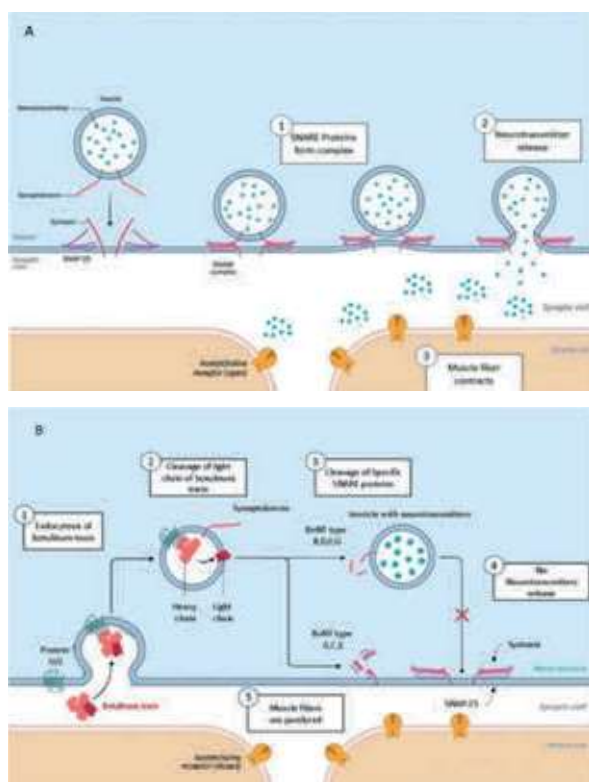


Figure 1 - Effects of botulinum neurotoxin type A (BoNT/A) on neuronal cells. a) Physiological function of the nerve terminal, which releases the neurotransmitter acetylcholine during an electrical impulse via fusion (exocytosis) with the presynaptic membrane; b) Blockade of acetylcholine exocytosis induced by the entry of botulinum toxin into the neuron (created with BioRender.com).

If this effect were confirmed in humans, it would represent a disruptive innovation, with the significant advantage of being immediately deployable. In fact, its mechanism of action is independent of the toxin serotype involved, thus eliminating or drastically reducing the time required to identify the specific type and subtype of BoNT for the production of antisera (which are associated with known risks of individual hypersensitivity), the need for *in vivo* (mouse bioassays), and the costs of prolonged supportive therapies.

METHODOLOGY

The SPES project is structured in two phases. The first phase (1/2) involves the synthesis and analysis of Ebselen in accordance with the guidelines required for its production under Good Manufacturing Practice (GMP) conditions. The newly synthesized compound was tested in animal models, and the results were compared with those previously obtained using commercially available Ebselen (intended for preclinical studies, not in humans). The second phase will consist of a Phase 1 clinical trial on healthy volunteers. If the data obtained from human trials are confirmed, the next phases of the clinical study will be developed (phases 2-3) (Figure 2).

The optimization of the synthetic method and the production of the active pharmaceutical ingredient (API) were carried out by Lundbeck Pharmaceuticals Italy (LUPI). To assess its quality, the newly synthesized Ebselen was analyzed using Ultra Performance Liquid Chromatography (UPLC) at the laboratory of the Department of Pharmaceutical Sciences, University of Padua. Comparison of the quality profiles revealed a higher purity of the newly synthesized Ebselen compared to the compound used in previous preclinical studies. Furthermore, *in vitro* studies on primary cerebellar granule cell cultures confirmed the efficacy of the newly synthesized Ebselen in preventing cleavage of the SNARE complex components (SNAP25 and Synaptobrevin), thereby protecting the cells

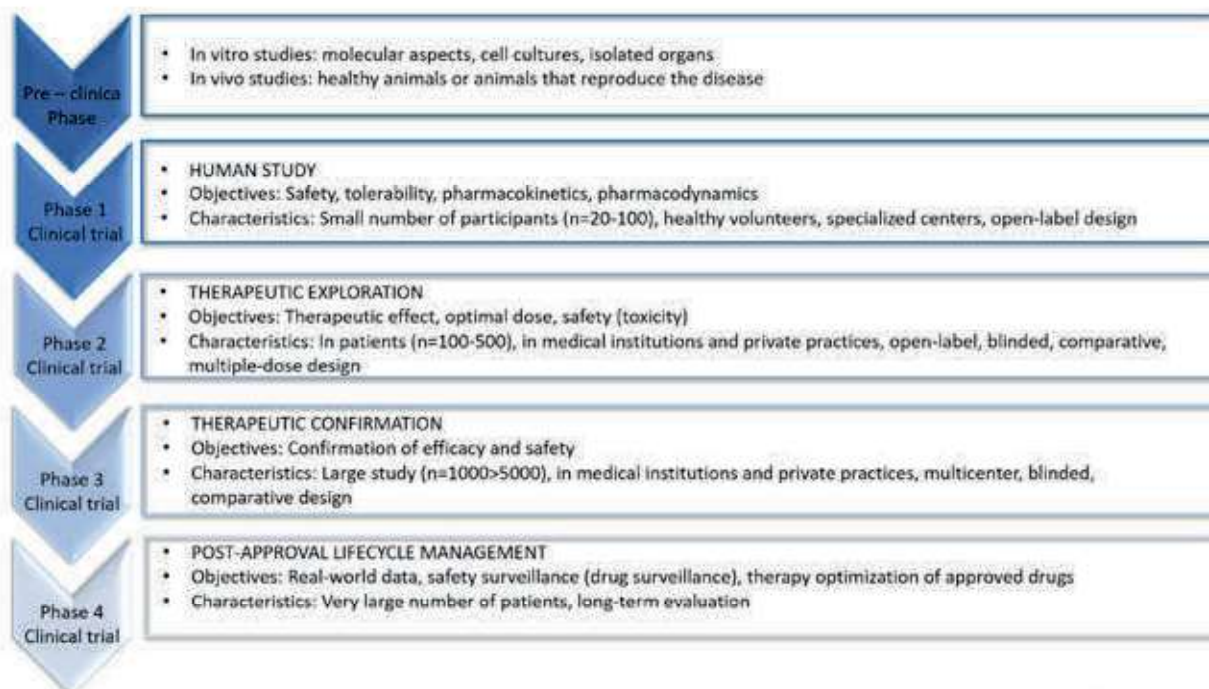


Figure 2 - Details on the pre-clinical, clinical and post-marketing phases of the trial.

from intoxication with botulinum neurotoxins type A and B (BoNT/A and BoNT/B).

In addition, the toxicity of the newly synthesized product was evaluated both *in vitro* and *in vivo*. For this purpose, a group of 5 mice was treated for 3 days with intraperitoneal injections of either commercial Ebselen or LUPI-synthesized Ebselen at a dose of 7.5 mg/kg every 12 hours. The results showed 100% survival in both groups (Figure 3).

Furthermore, *in vivo* the active ingredient reduces the duration of paralysis induced by type A toxin and reduces mortality by 50% in mice treated with a lethal dose of the same toxin (Figure 4).

POTENTIAL TECHNOLOGY APPLICATIONS AND EXPLOITATION

The SPES project is part of the research activities conducted by the Institute of Biomedical Sciences

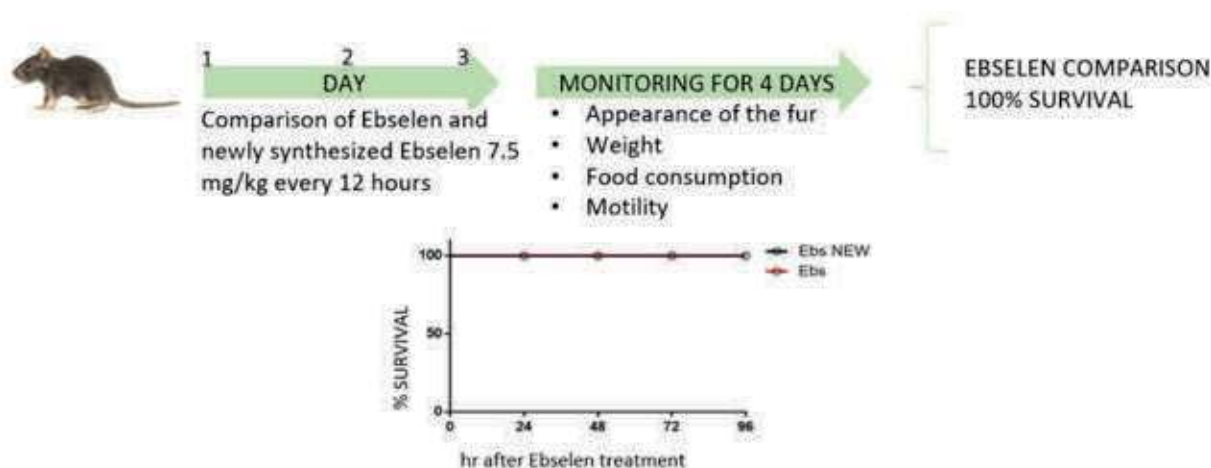


Figure 3 - Toxicity Test in mice.

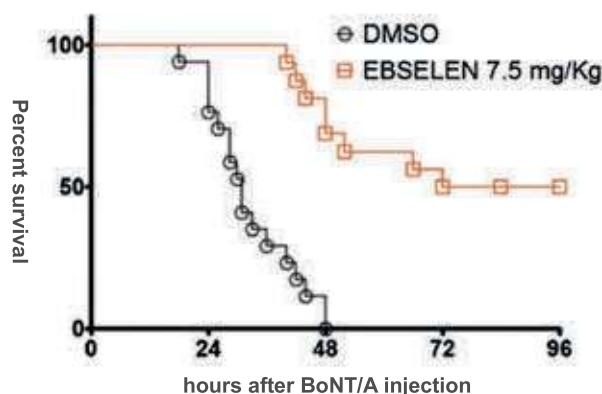


Figure 4 - Ebselen reduces BoNT/A lethality. Adult male CD 1 mice preconditioned with ebselen 7.5 mg/kg (n=15) or vehicle (n=15) were intraperitoneal injected with 2 × LD50 (lethal dose) of BoNT/A. The animals were monitored every 4 hr for 96 hr.

of Defense (formerly the Scientific Department of the Military Hospital), which began with the projects “Characterization and Identification of Botulinum Toxin-Producing Bacteria,” NIB1 and NIB2. These efforts led to the development of two patents: “Preventive or Therapeutic Administration of an Inhibitor of the Cellular Thioredoxin Reductase–Thioredoxin (TrxR–Trx) Enzymatic Complex to Block Botulinum Toxin Activity and Counteract Its Pathogenic Effects in Living Organisms” (Patent No. 102016000102615), and “Analytical Method and Kit for the *In Vitro* Detection of Botulinum Neurotoxins in a Sample” (Patent No. 10202000022054).

Confirmation of the inhibitory activity of the compound against botulinum neurotoxins in humans would enable the armed forces to be equipped with a preventive treatment for botulism. The SPES project has significant dual-use potential: on one hand, it neutralizes or reduces the threat of potential bioterrorism or military use of botulinum toxin; on the other, it offers a solution to a relevant public health issue, as Italy currently reports the highest number of botulism cases in Europe [11].

From an economic perspective, the project entails a substantial reduction in costs—including those related to supportive and antibiotic therapies and to the production of specific antitoxins—and the potential generation of profits through the drug commercialization and royalties.

CONCLUSIONS

The study on the mechanism of action of botulinum neurotoxins have enabled the identification of new strategies for the development of more effective inhibitors and antidotes than those currently available. The identification of Ebselen as an inhibitor of the TrxR–Trx system has led to the development of a novel preventive therapeutic approach for botulism. Ebselen—or more precisely, a medicinal product based on Ebselen—offers the advantage of being administered prophylactically, as it is readily available and its mechanism of action is independent of the botulinum neurotoxin serotype involved. As a result, the identification of the specific serotype, which is currently required for the production of serotype-specific antitoxins, will no longer be necessary, nor will the use of *in vivo* (mouse bioassays). Additionally, the costs associated with prolonged supportive therapies and individual hypersensitivity reactions could be significantly reduced or eliminated.

Finally, the SPES project has dual-use relevance: while Ebselen may prevent or mitigate the threat of potential military or terrorist use of botulinum toxin, it also provides a pre-exposure therapeutic option for the treatment of botulism in its various clinical forms (foodborne, wound, iatrogenic, inhalational, infectious). This approach offers a concrete solution to a public health concern that remains particularly relevant in certain regions of Italy.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

SPES	<i>Synthesis, Production and Clinical Trial of Ebselen</i>
NIB	<i>New Inhibitors for Botulism</i>
BoNTs	<i>Botulinum neurotoxins</i>
SNARE	<i>SNAP-25 Protein Receptor</i>
SNAP-25	<i>Synaptosomal-associated protein of 25 kilodaltons</i>
BoNT/A e /B	<i>Botulinum toxin type A and B</i>
CGNs	<i>Primary cultures of cerebellum granules</i>
TrxR-Trx	<i>Thioredoxin Reductase -Thioredoxin</i>
PNRM	<i>National Military Research Plan</i>
CDC	<i>Center for Diseases Control and Prevention di Atlanta</i>
LUPI	<i>Lundbeck Pharmaceuticals Italia</i>
UPLC	<i>Ultra Performance Liquid Chromatography</i>

KEYWORDS

Botulinum neurotoxin, Thioredoxin-Thioredoxin reductase, inhibitor, Ebselen, botulism, clinical trial.

PROJECT INFORMATION

PNRM number:	a2020.CT010
Organization:	Directorate General of Commissariat and General Services (COMMISERVIZI)
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The use of non-ionizing electromagnetic radiation has greatly increased in recent years, both in military and civilian applications. As a result, there is a growing research interest in the biological effects associated with exposure to this type of radiation. During the previously PNRM founded projects, GREAM and GREAM 2, the cytotoxic and genotoxic damage was evaluated in human cells *in vitro* exposed to electromagnetic fields used in military applications.

Instead, the present research focused on the study of a military population working in an environment in which radiofrequency sources are present. The project consists of two different parts: a) identification and characterization of the exposure conditions through computational simulations; b) evaluation of possible biological effects in a group of soldiers occupationally exposed to radiofrequency and in a control group of “non exposed” soldiers using a multimethodological approach already used in the two previous PNRM projects. During the phase 1 of the project the most critical source, from the exposure point of view, was identified. The characteristics were identified and a first quantification of the exposure level was carried out. In addition, the first biological analysis was performed on a group of “non exposed” soldiers. The preliminary results are reported.

INTRODUCTION

Electromagnetic fields (EMF), particularly in the radiofrequency (RF) range, is increasingly employed in military contexts, resulting in growing exposure among personnel. To date, the only RF-induced biological effects recognized and accepted by the scientific community are thermal effects. Although several investigations have addressed the potential non-thermal effects, this subject remains controversial and debated. Moreover, existing studies are predominantly *in vitro*, whereas biomonitoring studies involving occupationally exposed persons remain limited.

The specific objective of this project is to translate the knowledge acquired from our previous *in vitro* research into a study involving a group of military personnel professionally exposed to RF, with the final goal to contribute to health protection and safety of individuals working in environments where RF sources are

present. An innovative aspect of this study is the fact that, for the first time, the exposure of military personnel is characterized using anatomically realistic human models and computational simulation platforms. An additional original approach is that this research involves transcriptome analysis using Next Generation Sequencing (NGS) technology to identify possible genes ‘sensitive’ to this radiation. This study could contribute to the revision of current occupational exposure regulations, as well as health and safety protocols for military and civilian personnel.

TECHNICAL BACKGROUND

In recent years, due to rapid technological advancements, there has been an increasing use of devices and systems employing EMF radiation, particularly RF, in the military area. Radar, tactical microwave systems, jammers, satellite communication systems, and other devices based on

this type of radiation play a significant role in modern military operations. Moreover, the recent expansion of RF applications includes support for technologies such as drones and remote systems. This broad range of military RF applications highlight the urgent need to assess potential health risks for personnel occupationally exposed to RF radiation. Although there are national regulations on occupational exposure limits to EMF, based on European recommendations and international guidelines (ICNIRP), these predominantly focus on thermal effects, which are scientifically well documented. Furthermore, biomonitoring studies on individuals occupationally exposed to RF radiation are very few and then their contribution to the development of such regulations and guidelines is limited.

The goal of GREAM 3 project is to implement the previous researches performed in the context of GREAM and GREAM 2 projects on human cells, with a biomonitoring study on a military population which use RF devices or work in the presence of equipment emitting RF radiation, employing a dual approach: an “engineering” method involving the characterization of exposure conditions by simulating realistic scenarios, and a “biological” approach with the evaluation of potential genotoxic and/or cytotoxic effects on the military individuals studied.

METHODOLOGY

A) Exposure characterization

The 3D in silico human model, the EMF source model, and the relative positioning between the source and the human model were selected. The exposure scenario was then simulated using a computational calculation platform (Figure 1). Finally, the levels of electromagnetic power absorbed per unit mass (Specific Absorption Rate – SAR, W/kg) of the human model were evaluated. The maximum value obtained was 1.204 W/kg per Watt of input power to the source antenna.

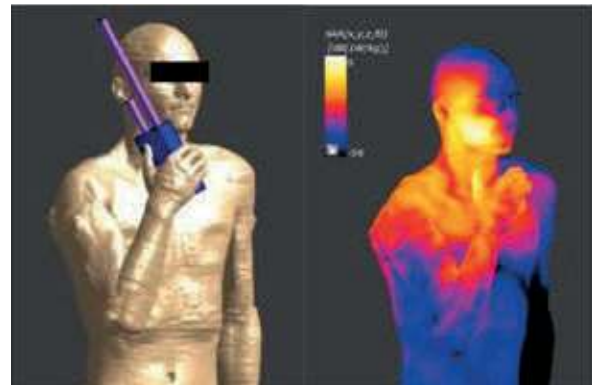


Figure 1 - Example of SAR distribution (W/kg), normalized to 1 W of input power to the antenna, generated by a radio SDR-HH (Software Defined Radio hand-held)* on 3D human model.

* Selected among the identified EMF sources as the potentially most critical from an exposure point of view, based on proximity to the body, duration, used frequency and the dose of electromagnetic power absorbed by human tissues.

B) Biological Analyses

After defining the recruitment criteria, 12 “non exposed” military personnel were enrolled. Peripheral blood samples from these individuals were analyzed with different biological markers, the same already used in previous in vitro projects (Figure 2). Gamma H2AX foci

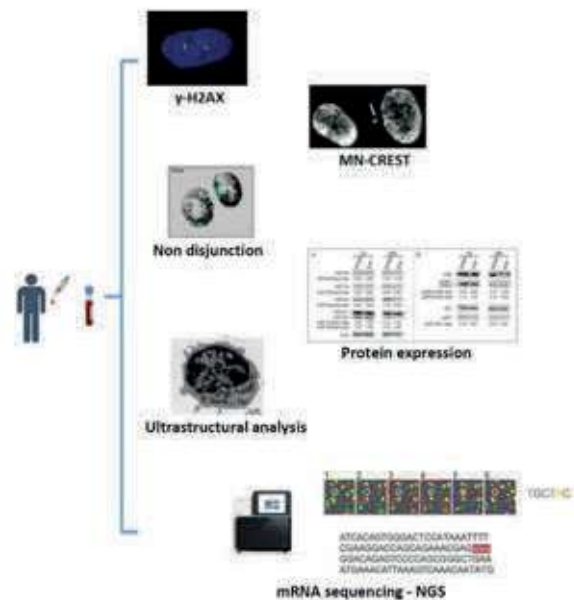


Figure 2 - Biological analysis performed on human lymphocytes.

analysis was performed to detect possible DNA doublestrand breaks. The micronucleus (MN) test in binucleated cells with CREST fluorescence staining was carried out to assess po-

tential chromosomal damage and its nature, whether due to chromosome loss or formation of acentric fragments. Additionally, to identify mis-segregation events, chromosomal non-disjunction analysis was performed in binucleated cells using Fluorescence In Situ Hybridization (FISH) with centromeric probes specific to three pairs of chromosomes.

The results obtained from these analyses were consistent with those reported in the literature for non exposed populations. Moreover, the expression of some heat shock proteins and proteins involved in signal transduction was examined, showing heterogeneity in the expression among the analyzed samples of non exposed subjects. Ultrastructural analysis of lymphocyte cells performed by electron microscopy showed well-preserved morphology within normal limits. Finally, from the mRNA sequencing of lymphocytes were obtained sequences suitable for subsequent bioinformatic analysis to study whole gene expression profile.

POTENTIAL TECHNOLOGY APPLICATIONS AND EXPLOITATION

The results obtained from this research could improve the scientific understanding of the biological effects of RF radiation. Furthermore, our study may contribute to the revision of current regulations on occupational exposure limits, potentially leading to the expansion of health protocols and guidelines for health protection and safety of mil-

itary and civilian personnel working in presence of devices emitting such radiation.

CONCLUSIONS

In phase 1 of 2 of GREAM 3 project the potentially most critical source from an exposure perspective was identified and characterized, and the exposure scenario was defined. Subsequently, the Specific Absorption Rate (SAR) levels in the tissues of the human model were calculated. The maximum input power to the antenna identified will be compared in Phase 2 with the limits established by guidelines for human exposure to EMF. In addition, the variability of exposure will be quantified by changing the simulation parameters. In Phase 1, the results obtained from the different biological investigations on the first recruited “non exposed” military personnel are consistent with those observed in non-exposed populations. Furthermore, heterogeneity in the expression of heat shock proteins and some signal transduction proteins assessed in the analyzed subjects was highlighted.

During the next phase of the project additional soldiers from the “non exposed” group and soldiers of the “exposed” group will be examined.

The results obtained from the two groups will finally be compared. The mRNA sequencing data will be processed through bioinformatic analysis to identify any differentially expressed genes and their functions, if known, in order to gain insights into the biological processes involved in the response to RF exposure.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

EMF	<i>Electromagnetic fields</i>
RF	<i>Radiofrequencies</i>
NGS	<i>Next Generation Sequencing</i>
CREST	<i>Calcinosis, Raynaud's phenomenon, esophageal dysmotility, sclerodactily, teleangectasia</i>
SAR	<i>Specific Absorption Rate</i>
ICNIRP	<i>International Commission on Non-Ionizing Radiation Protection</i>

KEYWORDS

Electromagnetic fields, Radiofrequencies, biomonitoring, professional exposure, computational analysis, biological analyses, mRNA sequencing.

PROJECT INFORMATION

PNRM number:	A2018.055
Organization:	Direzione Generale di Commissariato e di Servizi Generali (COMMISERVIZI)
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Antimicrobial resistance represents a serious global health threat. This phenomenon has a significant socioeconomic impact, especially in hospitals and military theaters of operation, where patients undergoing invasive therapies are more susceptible to resistant infections. The AGRINTO project aims to implement next-generation sequencing and evaluate its impact on the analysis of resistant strains. The results show that this technology can accurately and deeply characterize drug resistance profiles, making it possible to replace conventional approaches with molecular methods and next-generation sequencing. The wealth of information generated by high-throughput sequencing will also facilitate the identification of novel forms of resistance and provide a deeper understanding of the underlying mechanisms, thereby facilitating the development of novel therapeutic strategies. Technological advances in this field, now exemplified by third-generation sequencing, have already laid the foundation for performing analyses directly at sites of interest, with realtime data processing.

INTRODUCTION

Antimicrobial resistance (AMR) is one of the most serious threats to global public health (1). Antibiotics were initially seen as a definitive solution to bacterial infections. However, their excessive and inappropriate use has led to the selection of resistant strains (2). The issue is especially salient in nosocomial contexts, where invasive diagnostic and therapeutic procedures can facilitate the entry of pathogenic microorganisms. These microorganisms can often become more virulent due to the fragility of patients, which can result in fatal infections (3, 4). According to the World Health Organization (WHO), in 2019, AMR was directly responsible for 1.27 million deaths and contributed to the deaths of approximately 5 million individuals (5). The acronym ESKAPE is used to denote six major multidrug-resistant nosocomial pathogens: *Enterococcus faecium* (vancomycin-resistant, VRE), *Staphylococcus aureus* (methicillin-resistant, MRSA), *Klebsiella pneumoniae* (carbapenemase-producing), *Acinetobacter baumannii* (often carbapenemase-resistant), *Pseudomonas aeruginosa* (multiresistant, with efflux and biofilm mechanisms), and *Enterobacter spp.* (beta-lactamase-producing) (6). In the context of mil-

itary operating theaters, the issue of antibiotic resistance warrants particular consideration, as infections that are resistant to standard antibiotic treatments have the potential to complicate surgical interventions. This complication can arise in scenarios where surgical procedures are deemed to be invasive and, consequently, are susceptible to the development of resistant infections. This potential complication has been documented in the medical literature and is supported by several studies demonstrating the occurrence of such infections in military contexts. (7-9). In order to address this phenomenon, it is imperative to employ rigorous research methodologies such as the study of AMR strains, their geno-phenotypic characterization, and the in-depth analysis of antibiotic resistance determinants (resistome). These approaches are essential for comprehensive surveillance and elucidating the molecular mechanisms underlying antimicrobial resistance. Next-generation sequencing (NGS) technologies have enabled the high-resolution characterization of genes involved in antibiotic resistance, which is a crucial step in the development of more effective therapies (10). The AGRINTO (Genomic Analysis of the Resistome of Nosocomial Infections in Theaters of Operations)

project is an initiative that aims to implement the use of the latest generation of sequencing technologies in the analysis of antibiotic resistance in bacterial strains collected within the Italian territory.

The project's primary objectives include the comparison of data with classical methods and the evaluation of the usability of the new methods in military theaters of operations.

TECHNICAL BACKGROUND

Addressing the issue of antibiotic resistance necessitates the characterization of infectious agents according to standard methodologies employed by analytical laboratories. Classical tests, such as phenotypic tests, have been developed to predict a bacterium's capacity to produce resistance enzymes, such as β -lactamase, or its propensity to form a biofilm. Other quantitative tests, such as the E-test or the MIC (minimum inhibitory concentration), can assess the amount required to inhibit bacterial growth. Phenotypic or genotypic analysis can be used to predict whether a *Staphylococcus aureus* strain is resistant to methicillin. The presence of the *mecA* gene, which is indicative of resistance to beta-lactams, suggests the use of antibiotics such as vancomycin, linezolid, or daptomycin. In the event that the strain exhibits multidrug resistance to multiple antibiotics, treatment with broad-spectrum antibiotics such as tigecycline or, in cases of severe infection, ceftobiprole, a fifth-generation cephalosporin, will be necessary. Genetic tests, such as the polymerase chain reaction (PCR), the quantitative polymerase chain reaction (qPCR), and genotypic microarray, have been developed for rapid and accurate detection of the presence of genes or mutations associated with resistance. qPCR analyses are a valuable tool for the detection and quantification of genes such as *bla*NDM, which is a carbapenemase gene found in *Enterobacteriaceae*. It should also be noted that a combination of genotypic and phenotypic testing may be required, as a bacterium may possess genes associated with resistance yet fail to manifest them. A *Klebsiella pneumoniae* strain may possess the *bla*KPC gene (genotype), yet its ex-

pression may vary. In the bacterium *Pseudomonas aeruginosa*, the expression of efflux pumps is inducible only in the presence of antibiotics. The advent of next-generation sequencing (NGS) technologies has enabled the accurate characterization of the resistome, thereby facilitating more targeted and effective management of nosocomial infections caused by pathogens. This approach, when used in conjunction with classical methods, is proving to be increasingly advantageous. It is imperative for the field of personalized medicine, as it facilitates the appropriate utilization of antibiotics and mitigates the emergence of novel resistant strains.

METHODOLOGY

The strain collection, conducted in two successive phases, was carried out in two distinct hospital units. At one of the sites, both Italian and North African migrant strains were isolated. For purposes of illustration, a concise description of the collection executed in the second phase will hereby be presented. A total of 34 strains were collected, 9 of which were isolated from migrants. These included 14 *K. pneumoniae*, 8 *A. baumannii*, 9 *P. aeruginosa*, and 3 *Enterobacter spp.* The identification of these strains was performed using MALDI-TOF spectrometry, and antibiotic sensitivity/resistance testing was conducted using commercial automated systems.

As illustrated in Figure 1, the graphs depict the profiles of sensitivity (S, green), resistance (R, red), intermediate sensitivity (I, yellow), and undetermined (N.D., blue) of the collected strains.

Phenotypical analysis revealed that the isolates exhibited multidrug resistance (MDR) characteristics. Of particular note was the sensitivity to colistin: 92% in *K. pneumoniae*, 100% in *A. baumannii*, 85% in *P. aeruginosa*, and 66% in *Enterobacter spp.* No phenotypic differences emerged between strains isolated from migrants and local patients. In *Enterobacteriales* strains, the presence of carbapenemase resistance was investigated through the implementation of Real-Time PCR. The analysis revealed that all *K. pneumoniae*

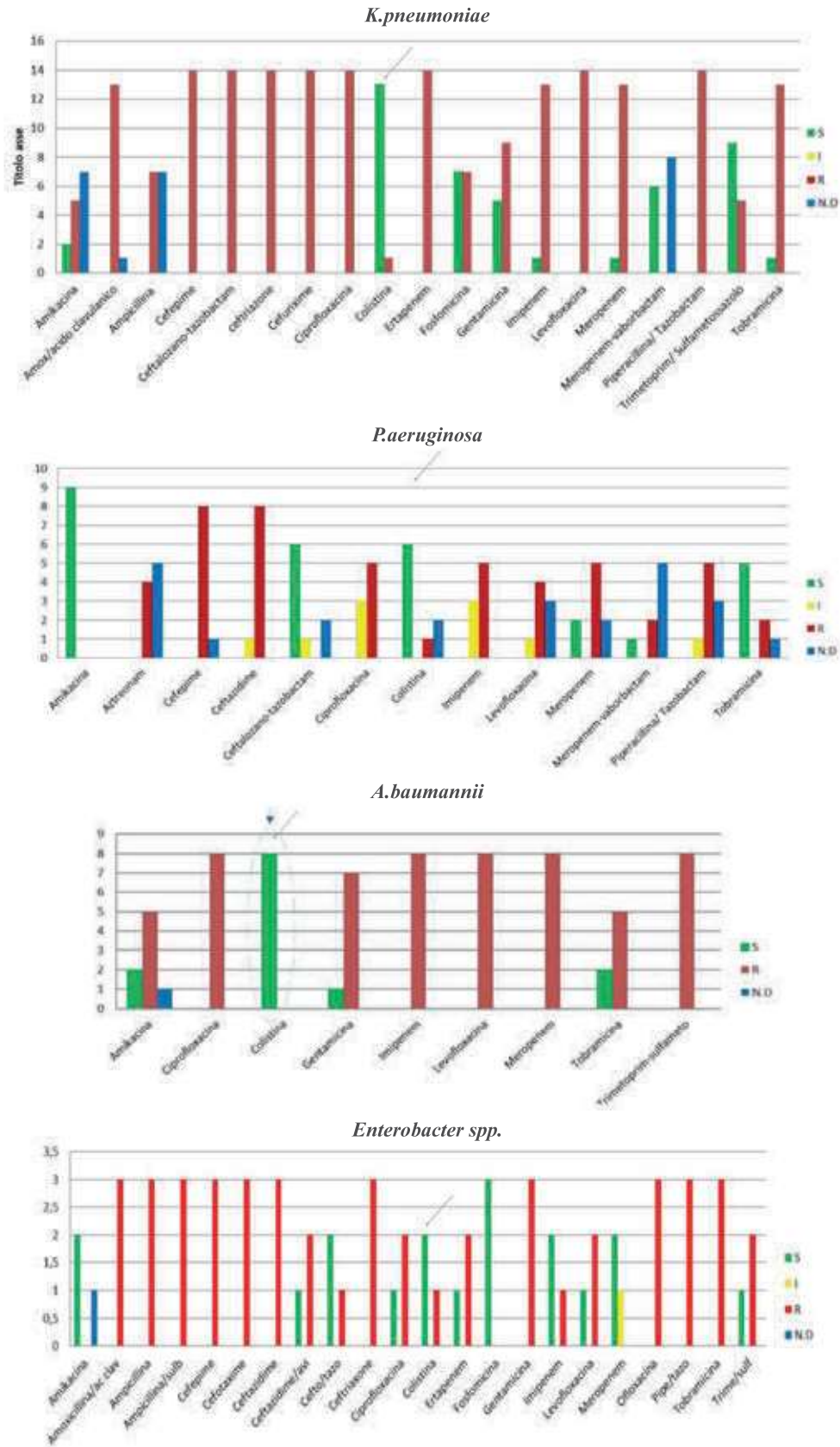


Figure 1 - Drug-resistance profile. Colistin sensitivity in all strains is highlighted.

	11	288	12	V3	24	V5	17	270	19	702	14	147	15	939	20	229	21	884	22	340	25	93	880	290	16	V2	18	V4	23	V8		
AK	R	R	S	S	R	R	R	R	R	R	R	R	R	S	S	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
GM	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
TM	R	R	S	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
IMP	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
MRP	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
CIP	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
P/T	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R

Figure 2 - Antibiogram on the strains of *A. baumannii*. In the ordinate the acronyms of the antibiotics used. S = sensitive; R = resistant. Color groups the origin of the isolate: green = sputum; yellow = bronchoalveolar lavage; pink = bronchoaspirate; gray = urine.

strains exhibited the capacity to produce carbapenemase *blaKPC*. A particular focus was given to *A. baumannii* in regard to its association with the XDR (extensively drug-resistant) phenotype. In vitro assays and virulence (biofilm formation) tests were conducted, revealing superior invasive capacity compared with reference strains. A subsequent commercial antibiogram confirmed that all but one of the strains were XDR (Figure 2).

Bioinformatic analysis of the data obtained with NGS confirmed the XDR genotype of these isolates, with the presence of the *blaOXA-23* gene (except for two strains) and the *blaOXA-66* variant, present in 67% of cases. These variants are prevalent in North Africa and Asia, suggesting an endemicity of this variant in Italy. All isolates carry the *blaADC* genes in the

different variants. As illustrated in Figure 3, an analysis of the distribution of resistance genes detected by NGS analysis in *A. baumannii* strains reveals the presence of *GyrA* S81L and *ParC* S84L mutations in the gene encoding gyrase and topoisomerase, respectively, in addition to the previously mentioned genes.

POTENTIAL TECHNOLOGY APPLICATIONS AND EXPLOITATION

Classical microbiological techniques and phenotypic antibiograms remain essential tools for the rapid identification of pathogenic strains and their drug susceptibility, especially in resource-limited clinical settings. However, the advent of next-generation sequencing (NGS) has opened new perspectives for the surveillance and molecular characterization of

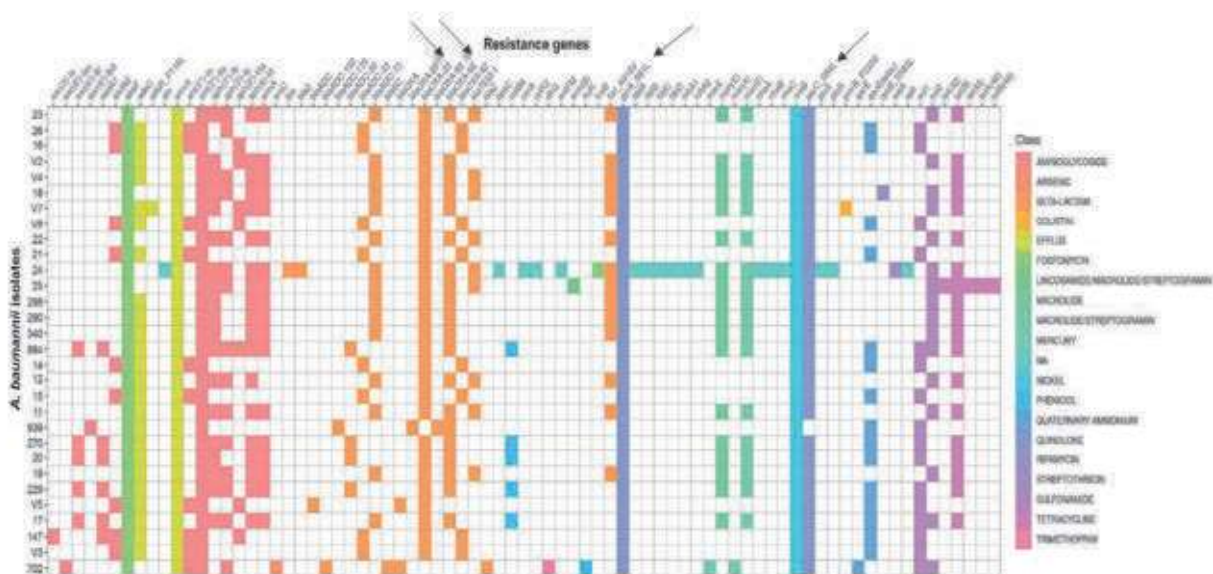


Figure 3 - The distribution of genes associated with antibiotic resistance in *Acetobacter baumannii* isolates has been detected by NGS. The ordinates represent the various strains of *A. baumannii*, while the abscissae illustrate the identified resistance genes that have undergone analysis. The application of colour-coding facilitates the identification of resistance to various antibiotic agents, including disinfectants. Heavy metal resistance and efflux pumps have also been reported.

resistant strains, enabling precise genotypic identification of resistance mechanisms and phylogenetic reconstruction to monitor their dissemination.

These findings carry significant implications for the operational environment of the armed forces. First, genetic characterization, performed in specialized laboratories by means of next-generation sequencing (NGS) technology, makes it possible to develop specific molecular methods that are also easily applicable in operational theaters. Techniques such as real-time polymerase chain reaction (PCR) or microarray analysis provide rapid and accurate results without any particular logistical criticality. While classical methods retain some degree of utility in specific instances, they are anticipated to undergo a gradual and complete substitution by molecular approaches in the near future. Third-generation sequencing technologies, such as those offered by Oxford Nanopore Technologies, are particularly noteworthy in this regard. These technologies have the capacity to obtain genomic sequences in real time, using portable instrumentation that can be readily adapted to complex logistical settings. This suggests that, in the absence of centralized laboratories, the analysis of multidrug-resistant pathogens can be conducted directly in the field, offering

CONCLUSIONS

Antibiotic resistance represents a major global public health threat today. According to projections by the World Health Organization (WHO), mortality rates associated with resistant infections are expected to rise. The WHO has also raised concerns about the insufficient allocation of research funding by many countries, particularly in relation to the molecular characterization of bacterial genes responsible for antibiotic resistance. In this study, a sample size of over 100 subjects was collected in two Italian regions, across two distinct hospital settings. The distribution of AMR species is consistent with the literature on the prevalence of the main strains responsible for antibiotic resistance (ESKAPE) in Italy and globally. In addition to the comparison of genotype and phenotype associated with antibiotic resistance, phenotypic and genotypic analyses were performed on the virulome (i.e., virulence gene content). Molecular techniques and next-generation sequencing confirmed the bacterial profiles initially identified by classical methods. Nevertheless, next-generation sequencing (NGS) molecular analyses fulfill a variety of functions. In addition to providing a genotypic/phenotypic match consistent with tra-



Figure 4 - Third-generation sequencing. The figure illustrates the compact spatial requirements of the nanopore technology, which encompasses both the chip and the laptop computer. These requirements are sufficient to facilitate the execution of sequencing procedures in real-time and in situ analysis.

significant strategic advantages, including the capacity for rapid in situ diagnosis, targeted therapeutic management, and biosurveillance.

ditional methods, they offer a comprehensive depiction of the resistome's organization, facilitate the identification of novel resistance genes, en-

courage research on new therapeutic targets, and contribute to the development of genomic surveillance strategies, which are imperative for containing the propagation of multidrug-resistant strains. These findings will facilitate the transition from classical methods, which are challenging to im-

plement in operational settings, to accelerated and precise molecular techniques. In the near future, third-generation, real-time in situ sequencing will supplant these molecular techniques.

The findings of this study have been published in two international journals (11, 12).

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

WHO	<i>World Health Organization</i>
AMR	<i>Antimicrobial resistance</i>
MDR	<i>Multidrug resistant</i>
XDR	<i>Extensively Drug-Resistant</i>
ESKAPE	<i>Enterococcus faecium; Staphylococcus aureus; Klebsiella pneumoniae; Acinetobacter baumannii; Pseudomonas aeruginosa; Enterobacter spp.</i>
VRE	<i>Vancomycin-Resistant</i>
MRSA	<i>Methicillin-Resistant</i>
MIC	<i>Minimum Inhibitory Concentration</i>
PCR	<i>Polymerase Chain Reaction</i>
NGS	<i>Next Generation Sequencing</i>
AK, GM, TM, IMP, MRP, CIP, P/T	<i>Amikacin, Gentamicin, Trimetoprim, Imipenem, Meropenem, Ciprofloxacin, Penicillin/Tazobactam.</i>

KEYWORDS

Antimicrobial resistance, ESKAPE, Next Generation Sequencing.

PROJECT INFORMATION

PNRM number:	a2017.129
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The SIMONA (Sistema Italiano Messa in Orbita da Nave) project is framed within the context of autonomous national access to space through the study and testing at scale of a space carrier extraction system to be launched from a naval system.

The extraction system, which uses the approach currently called “soft launch,” involves reaching a safe distance from the naval craft before the engines are ignited.

The project is divided into three phases.

In Phase 1, the extraction system capable of launching, at the established safety altitude of 80 m, a carrier of mass up to 60t and diameter up to 2.5m was designed.

Initial actions for securing the ship and its crew in the event of catastrophic events resulting from major malfunctions were identified, and the design of the scale prototype intended for experimentation was developed and finally analysed the market capturable by the launch system and its institutional use.

Based on the results obtained during Phase 1, three themes were explored in Phase 2:

- Development of the technology demonstrator and implementation of a series of tests culminating in two representative tests:
 - Test 1: Achieving dynamic conditions (exit velocity of the carrier from the extractor tube) close to those of the real 1:1 scale system.
 - Test 2: control of peak acceleration (8g) during launch.

Both tests were successfully performed using both a pneumatic thrust and a pyrotechnic charge. Test 1 demonstrates that the solutions adopted for the sabot, carrier stabilization system inside the tube, and methods to reduce friction are also suitable solutions for the velocity regimes encountered in the full-scale system. Test 2 demonstrates the ability to control thrust and limit it to the commercial satellite launch condition.

- Evaluation of the response of ship structures, modified according to the Phase 1 analysis, to the conditions of:
 - complete detonation of all carrier stages;
 - deflagration of the first stage;
 - fall of the first stage during handling on the ship deck;
 - accidental ignition of the first stage during stowage.
- Analysis of revenues and possible sources of funding in the case of performing launch activities from ship.

Phase 3 saw the development of:

- Extensive testing campaigns to obtain launch statistics for the purpose of detecting their repeatability and sensitivity, identifying and remediating any non-nominal effects.

- Integration of the launch system with a (standard and absolutely reliable) device to ignite the space carrier once it is extracted from the tube that can be side-by-side and compatible with the Safe&Arm systems of any launchable carrier from the extractor tube designed in SIMONA.

INTRODUCTION

The SIMONA (Sistema Italiano Messa in Orbita da Nave) project is part of the activities to respond to the national need for autonomous access to space achieved by launching a space launcher from a marine platform using the soft launch technique.

The soft launch technique, with the rocket not igniting inside the extractor tube, as is the case with hot launch, but only after egress, is recommended in launches from ship and will be adopted as an exclusive technique by the British Navy, partly because of the advantages it has over hot launch (30 per cent reduction on size and 50 per cent reduction on mass and 10 per cent increase on range).

Soft launch is used on the ground for large intercontinental ballistic missiles launched from wheeled vehicles, such as Russian SS-25 and Chinese DF-31. This technique has been exported from military-derived space launchers: the Russian-Ukrainian Dniepr (derived from SS-18) launched from silos, the Chinese Long March 11 (derived from DF-31) launched from ships.

For the latter, the cargo ship De Bo 3 was initially used (first launch June 2019, put 7 satellites into orbit), then an adapted platform (September 2020, 9 satellites) and finally a new dedicated platform (December 2022, 9 satellites).

The SIMONA Program also followed a similar evolution, moving from the assumption of using Garibaldi Ship as the launch vehicle hypothesized in Phase 1 to a dedicated platform, the subject of Phase 3.

The objectives of the SIMONA project during Phase 3 were:

- Completion of the construction of the demonstrator and subsequent preparation for the execution of the tests through the installation on board of a sensor to measure the attainment of the altitude envisaged in the tests and consequently provide an electrical signal to activate the missile's safety and arming system, thus commanding the pre-ignition arming of the first stage.
- Perform tests on the demonstrator in accordance with the configurations determined in Phases 1 and 2 and develop analysis of the results obtained.
- Developing costs of the naval system and performing a cost analysis for the use of a possible alternative naval platform.
- Analyse the economic viability of the autonomous space access system, based on existing market analysis and future projections.

TECHNICAL BACKGROUND

The primary problem that led to the genesis of the project lies in Italy's unavailability of an autonomous system for access to orbital space. For reasons of safety of the overflown populations, it is not possible to launch from a traditional platform placed on national soil, so the viable solution passes through the use of a mobile platform (air or naval) capable of being able to carry out the launch from international areas where this does not pose risks to the populations.

The naval solution appears particularly attractive because of its ability to handle multiple

launches and, because it can handle extremely high loads, to impose no special limitations on the mass at vehicle launch.

A critical aspect of using a naval platform, however, is being able to ensure the safety of embarked personnel under any nominal or accidental circumstances such as, for example, the catastrophic event of vehicle detonation upon first-stage ignition. Dealing with this type of event requires the development of special launch technologies not available in the national and European arena to date.

The proposed technological solution is to carry out the ignition of the carrier's first stage when it has reached a minimum safe distance from the naval platform, through the use of a cylindrical ejection tube. The safe&Arm system ensures that the carrier maintains the safe condition until the safe altitude is reached beyond which the propulsion system is placed in the arm condition and then the first stage engine receives the ignition command initiating the first step of the carrier's propulsive flight to the final orbit.

The minimum safe distance is an important parameter that the program aimed to determine: this distance is the one that allows excluding any catastrophic damage to the crew, even in the case of complete detonation of the launcher propulsion.

The proposal inherent in the extraction and removal system for a marine platform-based orbital launch system is, at the European level, an innovation. In addition, at the international level, the following main innovative aspects of the launch system are highlighted:

- development of an in-depth study of the detonation transient of large (300mm) solid propellant-based vehicles or engines and analysis of its consequences on the launching Naval Unit;
- use of a "manned" naval platform designed as a multi-mission platform (orbital launch mis-

sions, super/hypersonic cruise missions with or without recovery, missions using remotely piloted air or naval vehicles).

That being said, the ambitious goal of the project was to, on the basis of a preliminary design of the launch system, design, build, and test a demonstrator of the pneumatic system of vehicle extraction and removal from the naval platform and evaluate the economic viability both in the case of launch from Nave Garibaldi and from a specially designed alternative launch platform.

METHODOLOGY

The proposed program consists of 3 phases.

In the first phase, after an identification of the basic requirements and the characteristics of the potentially suffered detonation event, the analysis of the ship's vulnerability limit and the estimation of the minimum distance of the carrier away from the ship at the time of first stage ignition is performed.

Though detonation of the stages of a space carrier is a rather rare event but one that cannot be ruled out a priori at the time of first stage ignition, the shock and heat waves generated by the full detonation of the carrier were evaluated. The results were obtained by matching the mass of propellant contained in the carrier with an equivalent mass of TNT, and using the same principle, data on the fragmentation and fragment dynamics generated by the explosion were obtained.

For the purpose of the vulnerability limit assessment, the VULNUS Code was used with which the ship's structure (decks, bulkheads, interior rooms), its primary sub-assemblies (engine apparatus, generating apparatus, combat system), the functional chains that connect the sub-assemblies and whose integrity is required to perform certain missions, and the main AIREX-related damage mechanisms (blast, fragmentation, flooding, fire) were modeled.

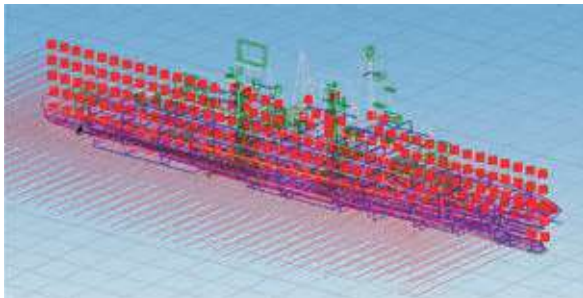


Figure 1 - View of the VULNUS model of Nave GARIBALDI.

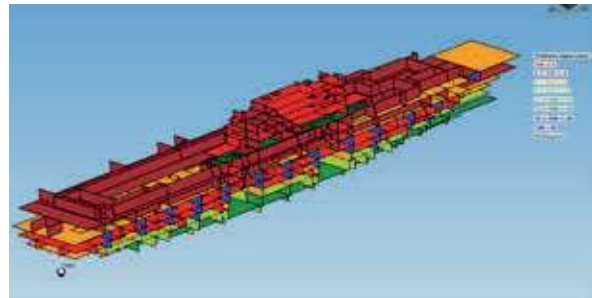


Figure 2 - Ship interior paneling.

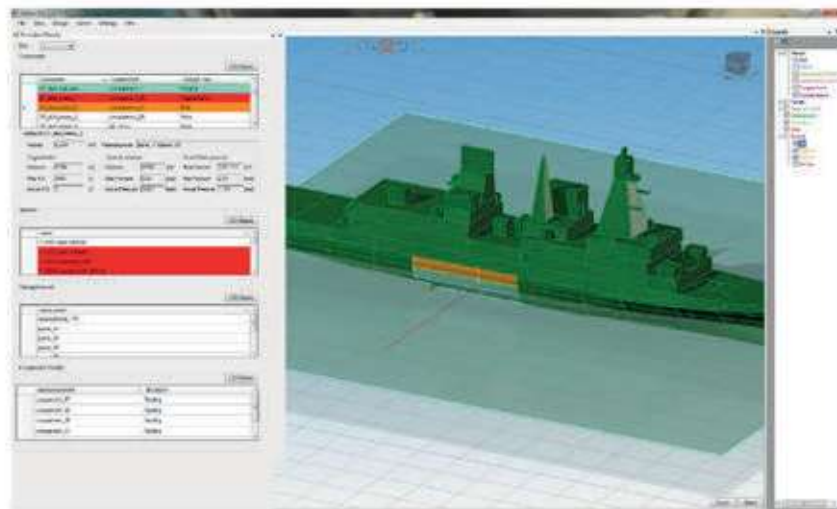


Figure 3 - View of the VULNUS model of Nave GARIBALDI.

The studies and simulations carried out leading to the conclusion that the minimum safety distances, in order to minimize any risk to property and people, are 80 m above the flight deck and 30 m behind the transom.

Based on the identified preliminary reference design of the launching system and the mentioned safety limits, both the design of the extraction and departure system and its demonstrator were carried out.

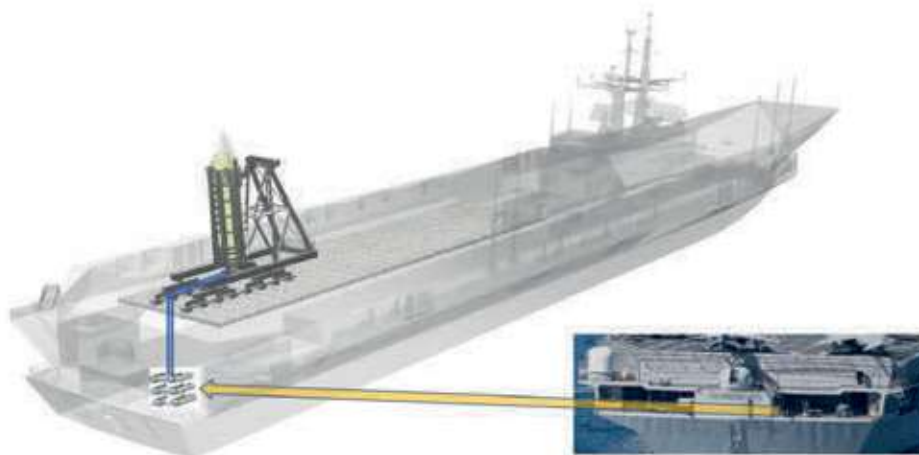


Figure 4 - Assumed positioning of the extraction/launch system.



Figure 5 - Extraction system: overall view.

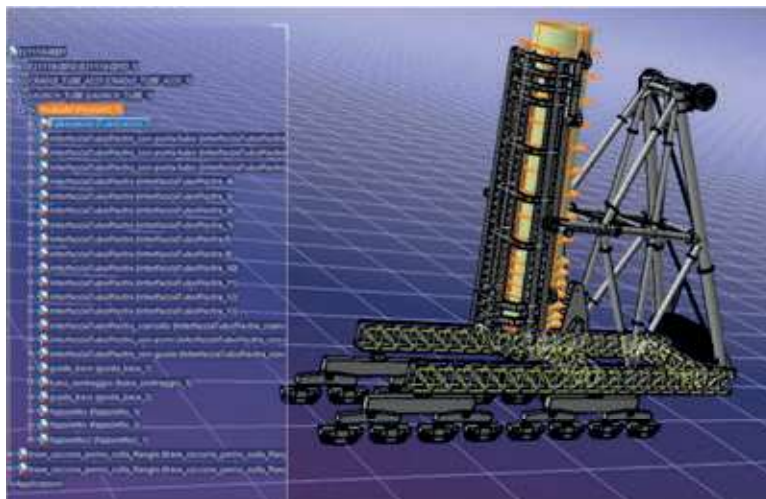


Figure 6 - CAD drawing of the launch tube.

In Phase 2, the vulnerability analysis of the ship platform is completed, evaluating the response of the ship structures, modified according to the Phase 1 analysis, to the conditions of complete detonation of all carrier stages, deflagration of the first stage, dropping of the first stage during handling on the ship deck, and finally accidental ignition of the first stage during stowage.

Insights from Phase 2 show that the extreme events analysed are such that they can cause even significant damage to the ship, but not compromise its buoyancy or integrity.

The first study presented, an evolution of the one carried out in the first design phase, shows that the pressure wave generated by an accidental detonation at 80 m altitude and 30 m aft is such as to permanently deform a significant portion of the flight deck in the aft area, with even very significant arrows in some areas above the hangar, characterized by significant spans. At the same time, the calculation rules out a global collapse of the flight deck, and consequently the longitudinal strength of the structure would remain largely assured since the central portion of the ship is essentially intact.

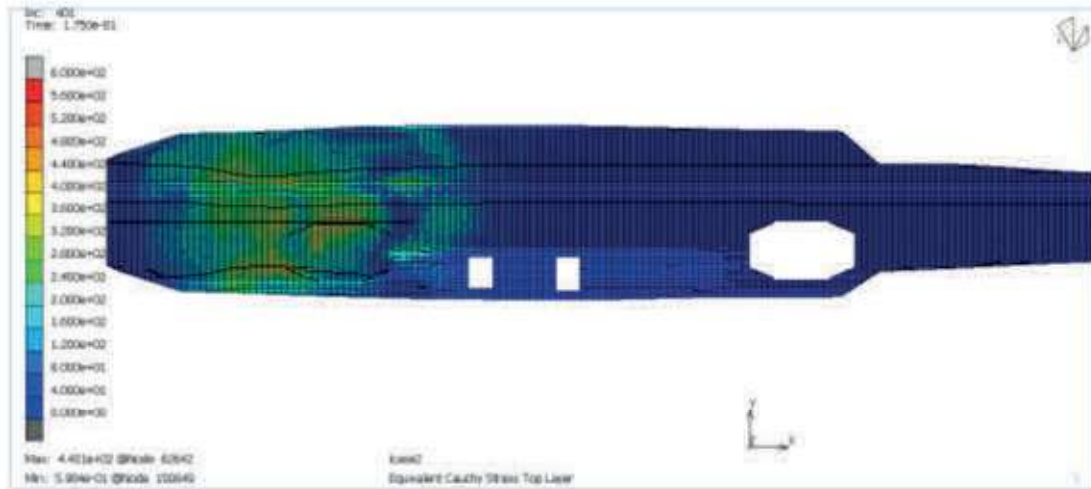


Figure 7 - Equivalent Cauchy voltages at detonation.

The flight deck proved capable of absorbing both the impacts of the fragments generated by the deflagration and the eventual fall of the first stage from an altitude of 19 m; in both cases the

structure would be permanently damaged while raising no doubt about the overall structural strength of the flight deck and ship.

Ultimately, the study showed that the first-stage

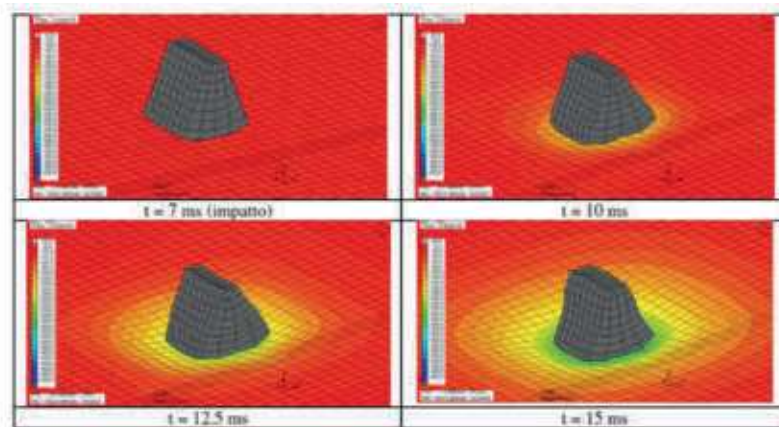


Figure 8 - Z-direction nodal displacement (mm) at impact from fragment.

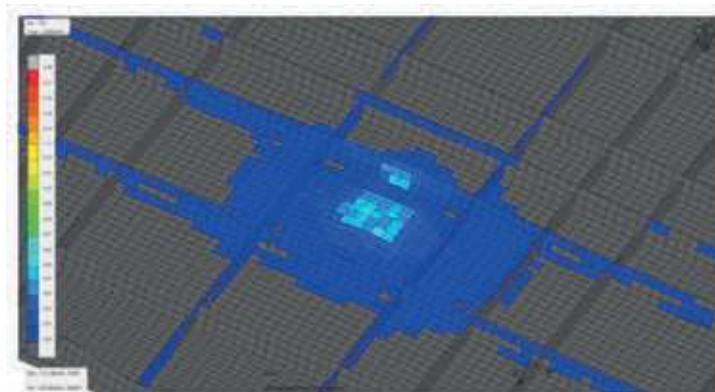


Figure 9 - Total plastic deformation of ship elements.

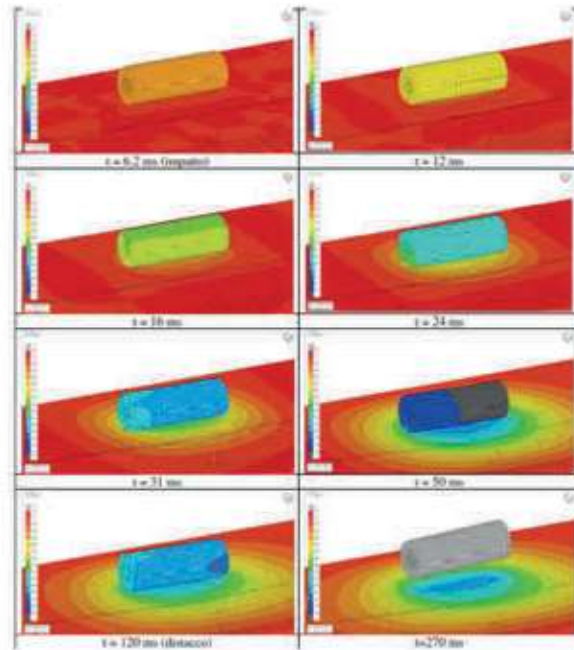


Figure 10 - Fall impact simulation for first stage.

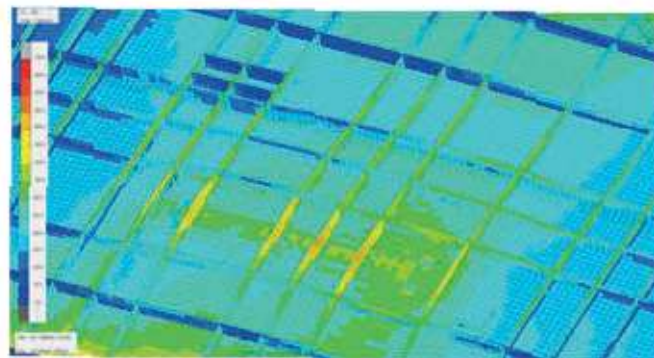


Figure 11 - Cauchy equivalent tension - Instant of maximum strain.

flare in the storage position does not directly tap the flight deck template, significantly reducing the thermal risk to structures in the event of ac-

cidental ignition of the propulsion system during stowage.

Therefore, the feasibility of the launch by Nave

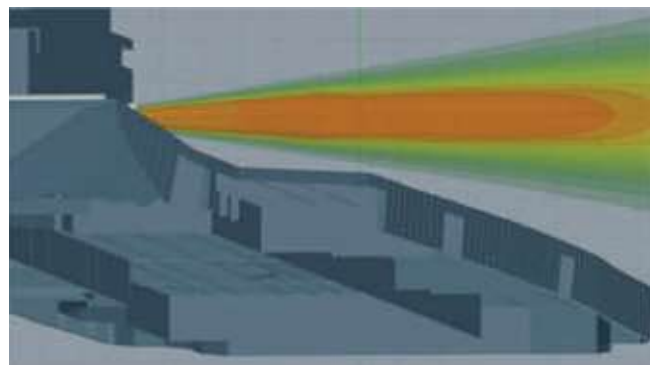


Figure 12 - Lack of interaction between direct first stage vane and ship structure.

Garibaldi is confirmed, provided that appropriate measures are taken for the sheltering of shipboard personnel detailed in the first design phase. In the final phase 3, the implementation of the demonstrator (WP1) is completed, concentrating efforts on the development of the Safe&Arm design, a crucial component whose task is to prevent unintentional or premature engine ignitions, ensuring that activation takes place only under predetermined conditions and in maximum safety. It was decided to implement an S&A system based on two complemen-

tary and independent technologies; an electronic critical parameter monitoring system that authorizes engine ignition only when all operating and safety conditions are met, and a mechanical safety release system designed to prevent unintended activation of the power plant. This dual protection ensures that even in the event of a malfunction or failure of either system, the other can intervene, ensuring safe operations and minimizing the risk of accidental ignition. The Safe&Arm (S&A) system developed for the SIMONA project successfully passed the

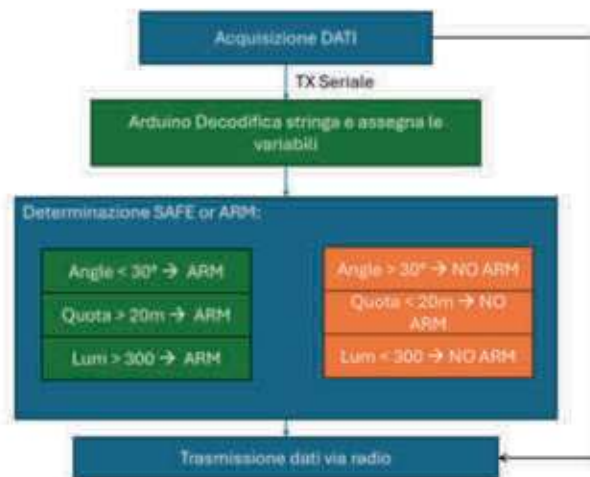


Figure 13 - Arming and ignition decision logic.

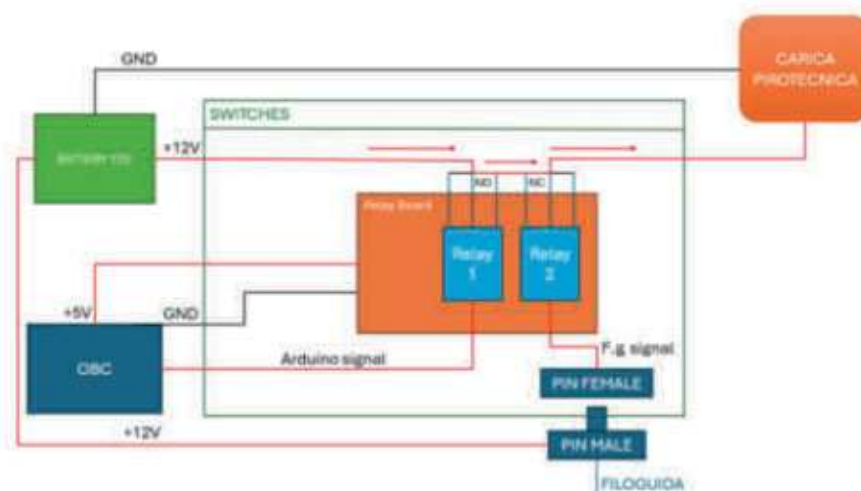


Figure 14 - Block diagram electronic and mechanical system.

tests, demonstrating high reliability in both arming and ignition of the pyrotechnic charge. The combination of the electronic sensors and the mechanical safety system ensured that mission parameters were met, preventing accidental ignitions and ensuring that activation occurred only under optimal conditions.

In the following WP2, tests are performed and the results analysed. The experimentation was carried out at the “Le Macchie” Barisciano (AQ) firing range, which saw a total of 108 launches in 12 campaigns divided into both pyrotechnic and pneumatic launches aimed at acquiring high statistics of range dispersions and accelerations.



Figure 15 - Experimental launch at “Le Macchie” firing range.

This was followed by estimating the costs required to convert Nave Garibaldi into a carrier launch unit and assessing the associated operating costs. This analysis was carried out on two fronts, on the one hand assessing the costs of adapting Nave Garibaldi to integrate the launch system (Non-Recurring Costs), and on the other hand assessing the operating costs of implementing a launch mission (Recurring Costs). The analysis was based on the findings of the launch-

er integration study on Nave Garibaldi developed in previous phases of the project.

Based on the analysis, it appears that the transformation of Nave Garibaldi into a platform for launching launchers to put satellites into orbit implies an engineering effort estimated at 75,000 h and a transformation timeline of 24 months, for an indicative cost of:

- 150 mln € in terms of Non-Recurring Costs;
- 26 mln € in terms of Recurring Costs on each launch.

Furthermore it was conducted the analysis and design study of an alternative naval platform in terms of defining the master plan and capacity plan, structural analysis and weight estimation, defining loading conditions and stability assessment, carrying out hydrodynamic calculations (towing strength and seakeeping), and estimating construction costs.

Starting with the functionality analysis of the unit, by analysing the general plan and the capacity plan, the main dimensions (146.4 m length, 36 m width, and 6 m height), an estimate of the hull weight (approximately 3700 to 4200 t depending on the configuration), and the sizing for the local load resulting from launching were estimated.

The loading conditions were then defined and, based on these, stability assessments and hydrodynamic calculations related to towing resistance (functional for determining relative costs) and sea-tightness were carried out; in particular, it was verified that the freeboard during launching has a variation in accordance with current regulations.

Finally, hull construction costs were estimated (approximately 11 to 13 M€ depending on the configuration).

Finally, the project developed an economic viability analysis of both screened solutions.

Examination of the results obtained showed that the a realistic recurring cost estimate is 10.3 k€/kg in orbit using Nave Garibaldi compared to 4.4 k€/kg using the newly developed alternative platform.



Figure 16 e 17 - Rendering of the Unit.

This figure, together with the nonrecurring costs mentioned above, suggest that the option of using an alternative naval platform is always preferable to using Nave Garibaldi in terms of economic sustainability both in the short and medium/long term.

POTENTIAL TECHNOLOGY APPLICATIONS AND EXPLOITATION

The conceivable uses are multiple both in the purely military field and in dual use.

Regarding the military value, the system would allow Italy both the independent execution of orbital insertion missions of military satellites and a possible development of rapid deployment missions (Rapid Response Missions).

The extraction and launch system resulting from the SIMONA Project can be extended/supplemented by a super/hyper sonic sub-orbital launcher capability and also used as a launch station for remotely piloted vehicles.

The proposed extraction system could provide a solid foundation for eventual design and use of

both submarine and orbital vehicle launch systems from the Earth's surface (similar to what has recently been seen on Russian wagon or train launch systems).

From a dual-valence perspective, the proposed system, with current international rules, brings Italy, as the country hosting the launch system (i.e., the ship), into the ranks of countries with space access capabilities. In addition, the receding system designed and analysed during launch campaigns has numerous potential uses in the civilian arena; a point-to-point supersonic unmanned transport vehicle that would use a thrust booster to prime the super/hypersonic engine is cited as an example. The system would enable rapid deployment missions in the civil domain and in response to crisis or accidental events.

CONCLUSIONS

Analysing the commercial aspects, it is emphasized that the national capacity to launch small satellites, which can be characterized by not high costs due to the ability to execute multiple missions, constitutes an asset of high commercial attractiveness in the current perspective of dizzying increase in the demand for putting small civilian satellites into orbit. The naval platform launch approach, of which the proposed extraction system is the critical enabling element, is the only one that would allow Italy independent access to orbital space for payloads of significant mass (150Kg). The condition of possessing such a national capacity for orbital access would allow the Italian industry not to suffer competitive penalizations that would result if it had to depend on the purchase of launch systems internationally.

KEYWORDS

Rapid Response Missions, Space Access, Orbit, Satellites, Naval Launcher, Safe&Arm.

PROJECT INFORMATION

PNRM number:	A2019.041
Organization:	Direzione degli Armamenti Navali (NAVARM)
Responsible entity:	Scuola di Ingegneria Aerospaziale
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RESEARCH IN THE INTERNATIONAL CONTEXT



INTRODUCTION

In the context of international cooperation, both within Europe (mainly in coordination with the European Defense Agency - EDA) and NATO and outside Europe, also through lateral bi-/multilateral agreements, Italy supports and has had a significant and profitable

collaborative technological research activity (R/T) in place for years.

Among the research projects that can be considered exemplary of this R/T international cooperation activity, the following are highlighted in particular:

- *Cyber Electromagnetic Resilience Evaluation Environment (CERERE)*
- *Bionics for Veterans (BIOVET)*

The evaluation of the cyber effectiveness of a system is currently limited to manual attack simulation or assisted activities based on known procedures, offering partial evaluations limited to the expertise and knowledge of the analysis team at the time. This approach is unable to measure the effectiveness of the system against unknown attacks such as zero-days or the actual ability of the available countermeasures to adapt. **CERERE** (*Cyber Electromagnetic Resilience Evaluation Environment*) was created to overcome these limitations, proposing an automated framework based on the principle of resilience that can have a close relationship with the concept of “cyber effectiveness” in case of complex systems, such as critical infrastructures and military networks.

CERERE does not focus on known vulnerabilities, but on understanding the ability of the system to identify a potential attack by observing the generated cyber effects on all impacted sub-systems and to timely ensure the application of a CoA (Course of Action) able to block the final outcome. The framework is inspired by the Monte Carlo method through simulations performed in *wargame* style, where an attack and a defense module interact in a synthetic environment. One continuously generates kill chains, optimizing their effectiveness through heuristic algorithms, the other, when the chain is detected, chooses containment strategies using artificial intelligence to respond better and better to the identified attacks.

The approach was validated on two realistic scenarios: a power production network and a military tactical network of moving convoys. In both cases, CERERE was able to assess the actual resilience of the configurations and to identify potential optimizations, in terms of more accurate detections or more targeted or quicker intervention strategies, improving the overall effectiveness of the existing countermeasures.

INTRODUCTION

Interest in cyber resilience is a topic that is arousing more and more interest, driven by the growing dependence of military systems on COTS sub-systems and net-centric architectures in many cases based on tactical radio infrastructures. These factors have significantly expanded and diversified the scope of exposure and control in the event of cyber attacks [1,2,3]. As a result, it is common practice to conduct regular testing through *penetration testing* or *red teaming* [4], in order to identify any vulnerabilities or the possibility of circumventing certain se-

curity countermeasures. However, manual testing is time- and resource-intensive and requires highly skilled personnel [5]. For this reason, there has been a growing interest in automated tools called BaaS (Breach and Attack Simulation) which now include several tools, both open source and commercial [4,6].

The **CERERE** framework proposes an alternative approach to the state of the art, modeling attacks as effects on the system, instead of applying the actual exploits to exploit a vulnerability (the Procedures) that unfortunately is only applicable for what already exists. This

approach therefore limits the assessment to only observable procedures, which does not take into account what could be used in the future. CERERE allows you to assess the resilience of systems in their current configuration and to identify the most effective countermeasures, making offensive and defensive modules interact in a sequence of iterative simulations in which the procedure is not really executed, but the effects that this procedure generates are injected into the system, effects that are independent of the mode of exploitation of the vulnerability because they are linked exclusively to the Technique and Tactics of interest.

TECHNICAL BACKGROUND

While traditional approaches are effective in validating systems against known vulnerabilities [7,8,9,10,11,12], they rely on the execution of real procedures or known repositories of exploits, limiting the ability to evaluate complex scenarios and new kill chains. In particular, this becomes a significant limitation in the context of *Cyber Electromagnetic Activities* (CEMA), which often require attack chains composed of multiple techniques, often unknown, and adapted to specific technologies of the subsystems involved [13].

To overcome these limitations, the **CERERE** project proposes a new paradigm: shifting the focus from the technical execution of attacks to emulating the chained effects that these attacks generate on subsystems, regardless of the specific exploit techniques used, injecting into the synthetic environment all variations related to them (e.g. execution of a process, change of a user, creation of a new file). This approach allows for an assessment centered on the system's ability to detect such effects regardless of their specificity, rather than on recognizing the actual way in which it is allowed. In doing so, it is possible to verify whether the system under test has been designed to adapt and detect the attack technique at the behavioral level and thus restore the com-

promised capabilities within an acceptable time interval, or to inherently ensure the operational continuity of its critical functions by preventing the attack from impacting the system.

The combination of heuristic algorithms for attack generation, artificial intelligence models for the selection of countermeasures and a simulation environment structured like an automated *wargame*, makes it possible to systematically measure the *cyber resilience of the system* defined as “guaranteeing certain operational performance parameters over time”. Through multiple simulations with different configurations, it is possible to compare and quantify the effectiveness of one or more attack chains with respect to the response strategy adopted (CoA), using resiliency metrics specific to each application domain.

METHODOLOGY

The **CERERE** project aim to create a **TRL 5** framework demonstrator, consisting of five main modules that cooperate to automatically assess the resilience of complex systems, such as critical infrastructures and military networks, against *CEMA attacks*.

The **Synthetic Environment** replicates the system to be tested in order to assess its resilience against CEMA attacks. The **Adversary Emulation** module, based on heuristic algorithms, automatically generates kill chains composed of actions derived from the Mitre ATT&CK TTPs modeled as pre-conditions and effects, progressively improving the choice through successive iterations. The **AI-supported Response Emulation** module models the countermeasures that can be activated when compromises are detected. This module employs two types of agents: a trained one that selects responses based on observations, and an adaptive one that improves its capabilities over time. Simulation **Control** coordinates simulations, measures resilience outcomes, and directs the interaction between modules. Finally, the **Presentation Layer** provides

an intuitive interface for setting up simulations and analyzing results.

During a simulation, the user selects the scenario and parameters. The system automatically generates kill chains and responses, runs rounds, collects results, and evaluates resiliency against defined metrics.

The framework was validated in two scenarios: an electricity production network and a military convoy on the move.

In the first case, CERERE highlighted potential risks, such as loss of operations, and identified effective countermeasures. In the second, it detected vulnerabilities such as packet loss in the tactical network, selecting the most suitable defenses also according to time constraints. In both cases, the framework has proven its effectiveness in driving the optimization of defensive strategies.

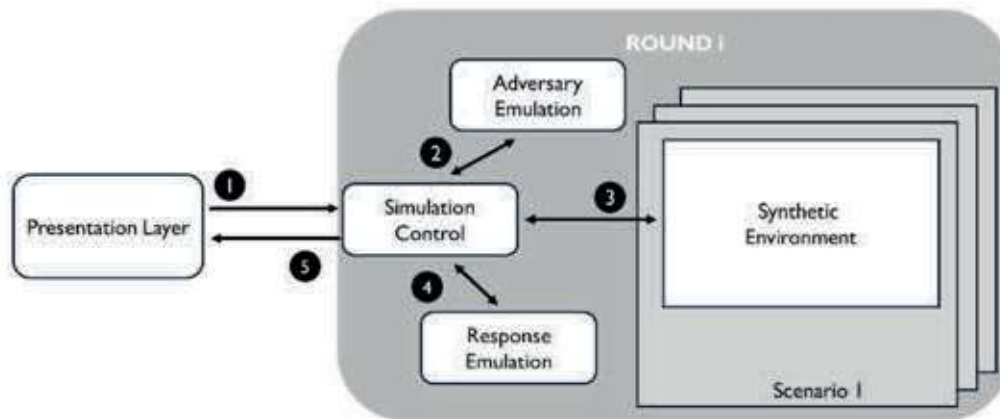


Figure 1 - i-th round of simulation in CERERE.

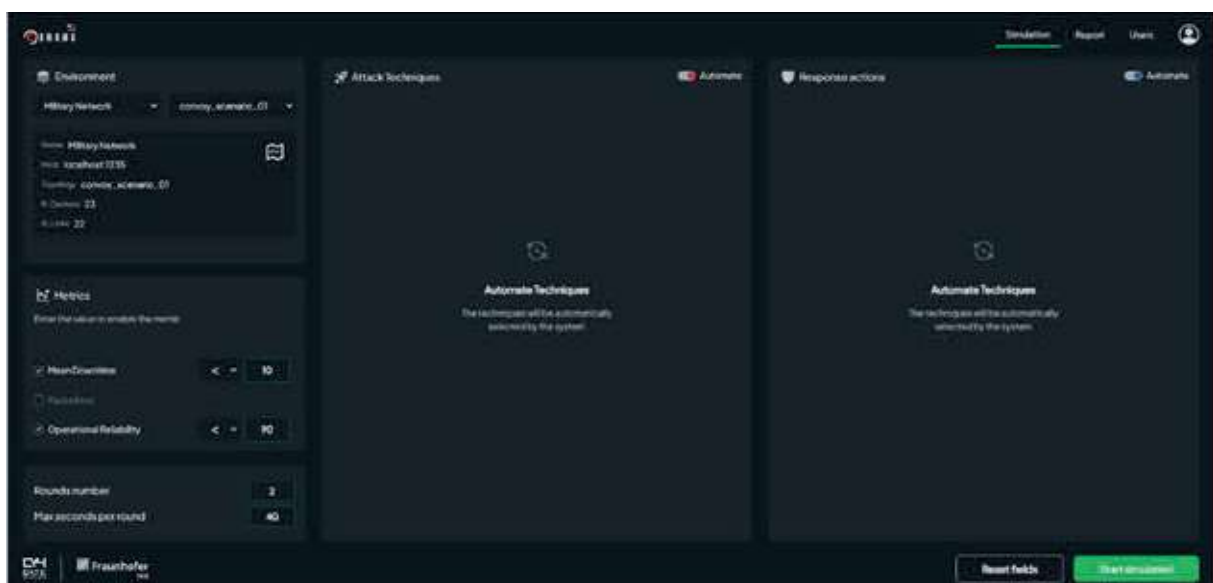


Figure 2 - CERERE's main interface that allows the user to configure the simulation to be performed by selecting the environment and metrics to be tested, the number of rounds and the times in which the environment must "resist". Finally, the user has the option to select automatic or manual attacks and responses based on the type of analysis of interest.

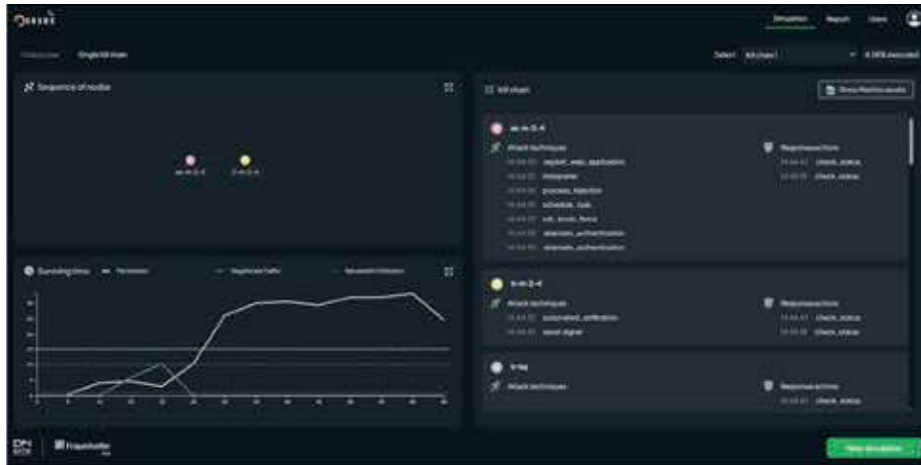


Figure 3 - Detailed interface of the results of the simulation performed with CERERE. In this case, the detail of kill chain 1 is shown. On the right side, the techniques performed by the kill chain are explained, indicating on which node of the system they were applied and in what timeframe. On the left side, on the other hand, the sequence of attacked nodes is shown, along with the graph that illustrates how the selected resiliency metrics (in this case, “illegitimate traffic” and “bandwidth utilization”) behave over time compared to the thresholds defined during configuration. In this example, the “illegitimate traffic” metric is violated.



Figure 4 - In this case, the system implemented different countermeasures than the Figure 3, in which only the action “check action”, corresponding to the intrusion detection system(IDS). In this simulation, additional actions were taken, such as isolating the compromised node and switching to jamming-resistant radio technology. While these countermeasures help mitigate the damage and recover communication, the system is still considered non-resilient, as recovery does not occur in the time frame deemed acceptable to ensure business continuity.

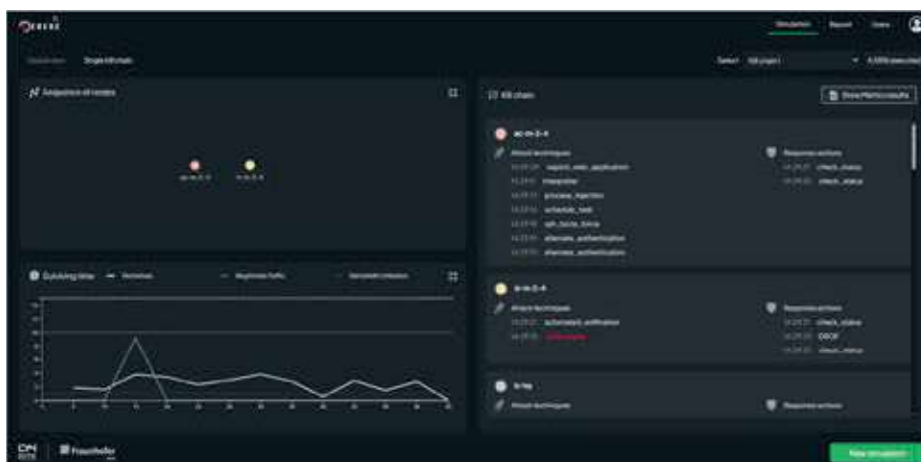


Figure 5 - In this last simulation, it is observed that the use of timely countermeasures, such as the identification and immediate blocking of malicious traffic (“DROP”), allows to prevent the success of the final “send signal” action, intended to exfiltrate the position to carry out jamming. Although the attacker managed to compromise two nodes, the system is still resilient, as the attack had no effect on communication capabilities.

POTENTIAL TECHNOLOGY APPLICATIONS AND EXPLOITATION

This is the first resilience assessment framework that changes the focus from executing attacks to generating the effects of attacks, assessing the final impacts on the operational performance of the entire system. This transformation defines resilience as the ability of a system to:

- Prevent the execution of specific actions (i.e., effects) on one or more critical subsystems, ensuring business continuity even in degraded conditions
- Detect attacker intent by observing the effects resulting from the chain of execution
- Incorporate efficient containment processes that can inherently block or intervene on compromised subsystems by applying CoA before the kill-chain has been completed

This innovative approach allows for a comprehensive assessment of resilience in critical or military environments, which are often vulnerable to unknown attacks, for which it would be difficult to have predefined attack procedures to test.

The framework demonstrator provided the first validation of the hypothesis that the attack space coincides with that of effects. Extended to other domains, the framework supports mission readiness, allowing you to assess the impact of a CEMA attack on your operation by analyzing its risks, system impacts, detection and response capabilities, as well as the design of recovery processes to promptly restore compromised subsystems.

CONCLUSIONS

The CERERE project designed a framework to test resilience and optimize defenses against attacks in synthetic environments representing complex multi-domain systems, such as critical infrastructures and military networks, which include not only IT/IoMT systems but also RF systems.

This framework combines several advanced modules, including execution environment modeling, attack generation, and response orchestration, and a simple-to-use user interface. The goal is to provide an automated and complete tool to assess how much a system can withstand one or more categories of combined attacks aimed at impacting the operational capacity of the system. It was tested on two real-world scenarios: an electricity production network and a military tactical network, gaining insight into how these systems were able to react to different types of attacks and which defense strategies were most effective in various situations.

CERERE is able to objectively measure the resilience of the system, thanks to algorithms that generate various sequences of attacks based on the effect they will have on the system. In addition, the framework uses AI to continuously improve defensive strategies (CoA), thus realizing a competition-based learning and evaluation method.

The project can be expanded to include new simulated environments and further refine the analysis capabilities to address a greater number of critical scenarios.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

AI	<i>Artificial intelligence</i>
CEMA	<i>Cyber-ElectroMagnetic Activities</i>
TTP	<i>Tactics, Techniques, Procedures</i>
CoA	<i>Course of Action</i>
BAAS	<i>Breach and Attack Simulation</i>

KEYWORDS

Resilience, Automated Effectiveness Evaluation, Kill-Chain Emulation, Red Teaming, Detection & Response, CEMA.

PROJECT INFORMATION

CatB Contract ID:	B PRJ RT 1079
Organization:	European Defence Agency
Responsible entity:	CY4GATE S.p.A.
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The BIOVET Project (Bionics for Veterans) is part of the bilateral agreement between the Italian Ministry of Defense and the U.S. Department of Defense, aimed at developing advanced robotic technologies for the rehabilitation of veterans with motor disabilities. This multidisciplinary collaboration involves multiple organizations and institutions: the Institute of Biomedical Sciences of Defense (ISBD), particularly the Defense Veterans Center (CVD) and the Bioengineering and Human Performance Section; the BioRobotics Institute of Scuola Superiore Sant'Anna in Pisa (SSSA), including its two spin-offs Prensilia S.r.l. (PRE) and Iuvo S.r.l. (IUVO); the University of Sassari (UNISS); and various U.S. institutions such as the Walter Reed National Military Medical Center, Spaulding Rehabilitation Hospital Boston, and the Uniformed Services University of the Health Sciences. Phase 1 of the project has consolidated Italian–U.S. collaboration, established experimental protocols, and developed prototypes for advanced prosthetics and exoskeletons. Preliminary results show the potential of these technologies to enhance users' quality of life, with promising applications in both clinical and operational settings.

INTRODUCTION

The BIOVET Project focuses on rehabilitative medicine to restore functional capacities through the development and testing of innovative robotic technologies for veterans with upper or lower limb disabilities. Its main innovation lies in developing upper-limb prostheses with advanced sensory feedback and customized lower-limb exoskeletons for motor rehabilitation, overcoming limitations of current technologies.

From an application standpoint, the technologies developed in BIOVET have dual use, with potential benefits for both military and civilian sectors. In military settings, advanced prosthetics and exoskeletons may support the physical recovery of injured personnel and facilitate their return to active service (Cooper et al., 2024). In the civilian context, robotic solutions can aid the rehabilitation of patients with motor impairments due to trauma or neurodegenerative diseases, representing a significant

advancement in biorobotics and assistive rehabilitation (Zhang et al., 2023).

TECHNICAL BACKGROUND

Combat injuries are a major challenge in rehabilitative medicine, significantly impacting veterans' quality of life and functional reintegration (Barry et al., 2009). Veterans with amputations and motor dysfunctions require advanced rehabilitative solutions to regain functionality and autonomy. BIOVET addresses this need by developing innovative technologies for motor recovery across two main research lines: FAST (Fusing Amputation Surgeries with prosthetic Technologies), which focuses on upper-limb prostheses with advanced neuromuscular interfaces to enhance control and reduce user fatigue, and BIONICRUS (Personalized Gait Rehabilitation for Veterans with Wearable Robotic Devices), aiming to improve lower-limb mobility through exoskeletons and prostheses that dynamically adapt to user movements, enhancing stability and reducing fall risk.

BIOVET adopts a multidisciplinary approach, integrating biomedical engineering, neuroscience, and advanced robotics. For FAST, key innovations include the development of a myokinetic interface for motor control and sensory feedback of a hand prosthesis, based on implanted intramuscular magnets. Usability studies are underway on the Mia Hand prosthesis developed by PRE, a dual-stiffness prosthetic wrist, and vibrotactile feedback systems. Additionally, advanced joint surgical training between Italy and the U.S. is planned to improve surgical and rehabilitative competencies, focusing on implementing the myokinetic control system. For BIONICRUS, major innovations involve machine learning-based control strategies for personalized motor support, testing of next-generation exoskeletons (e.g., hip and knee devices), and optimization algorithms to enhance user-device interaction, supporting motor adaptation over time.

METHODOLOGY

During Phase 1, experimental protocols were defined, and functional prototypes were developed for both research lines. In FAST, SSSA continued developing the myokinetic interface for motor control and sensory feedback, focusing on integration with users' myoelectric signals and material biocompatibility. PRE produced the Mia Hand prosthesis, which will be tested at ISBD and U.S. clinical partner centers to assess usability for upper-limb amputees. Additionally, the effectiveness of a variable-stiffness prosthetic wrist developed by SSSA will be evaluated to optimize comfort and functionality across different use scenarios. In BIONICRUS, SSSA and IUVO worked on developing advanced hip and knee exoskeletons, implementing predictive control strategies and algorithms to optimize motor support during movement. A gait phase estimation algorithm was developed, tested on biomechanical simulators, and validated with human subjects in controlled environments. Clinical testing protocols were defined in collaboration with ISBD, UNISS, and

U.S. partners to evaluate the technologies in rehabilitative and operational contexts.

UNISS also closely collaborated with ISBD and the Bioengineering Section to test prototypes using biomechanical motion analysis techniques. Research activities followed an iterative approach, including development, validation on experimental models, and data-driven optimization. The collaboration between partners allowed for integration of complementary expertise, maximizing the technologies' potential.

POTENTIAL TECHNOLOGY APPLICATIONS AND EXPLOITATION

The technologies developed in BIOVET have broad potential across multiple sectors.

In the military, robotic devices could support mobility in critical environments, such as combat zones or high-risk areas, improving endurance and reducing fatigue during prolonged missions. Advanced exoskeletons could enhance operational performance in demanding scenarios by providing targeted support for load carrying and movement in challenging conditions (Farris et al., 2023).

In the clinical sector, the innovations could transform rehabilitation for veterans and civilians with amputations or motor deficits by enhancing prosthetic solutions. Advanced neuromuscular interfaces may enable more precise and natural prosthetic control, leading to higher user acceptance and better integration into daily life (Gherardini et al., 2024).

In the biomedical industry, these technologies pave the way for innovative medical devices. The use of smart materials and advanced manufacturing techniques opens up new opportunities for customized prosthetic and rehabilitative solutions, improving patients' quality of life and treatment efficiency.

CONCLUSIONS

Phase 1 of the BIOVET Project marked a critical step forward in advancing technologies for motor recovery. The analysis of the state of the art pro-

vided crucial insights into existing technologies, laying a solid foundation for the development of innovative prostheses and exoskeletons. Defining the study targets and experimental protocols ensured that future activities will be focused and well-structured, optimizing approaches for patient groups and technologies under evaluation. Experimental data collected during the initial stages provided valuable guidance for shaping

research strategies, supporting the development and future validation of prototype versions to confirm the effectiveness of proposed solutions. Having achieved its initial goals, the project is now moving into Phase 2, which aims to refine and apply the developed technologies in clinical and rehabilitative settings. BIOVET is well-positioned to continue its progress and successfully address the next stages.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

BIOVET	<i>Bionics for Veterans</i>
FAST	<i>Fusing Amputation Surgeries with prosthetic Technologies</i>
BIONICRUS	<i>Personalized Gait Rehabilitation for Veterans with Wearable Robotic Devices</i>
ISBD	<i>Istituto di Scienze Biomediche della Difesa</i>
CVD	<i>Centro Veterani della Difesa</i>
SSSA	<i>Scuola Superiore Sant'Anna di Pisa</i>
PRE	<i>Prensilia S.r.l.</i>
IUVO	<i>Iuvo S.r.l.</i>
UNISS	<i>Università degli Studi di Sassari</i>

KEYWORDS

Biorobotics, motor rehabilitation, advanced prosthetics, exoskeletons, neuromuscular interfaces, personalized optimization.

PROJECT INFORMATION

PNRM number:	Not applicable
Organization:	Commiservizi
Responsible entity:	Istituto di Scienze Biomediche della Difesa
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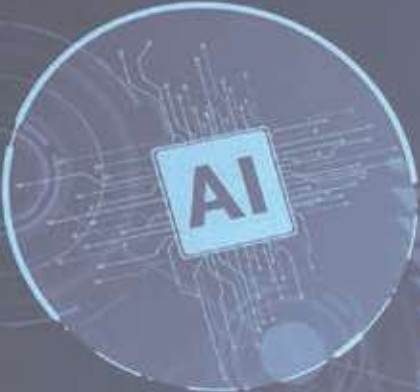
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STATISTICAL - FINANCIAL SUMMARY





STATISTICAL - FINANCIAL SUMMARY

DISTRIBUTION OF FUNDING BETWEEN PNRM AND INTERNATIONAL PROGRAMS

The breakdown between projects under the National Military Research Plan (PNRM), projects within the European Defence Agency (EDA), projects resulting from Framework Agreements

with the academic sector, technological research activities of the Defence Test Centres and international programmes (multilateral and bilateral) for the year 2024 is shown in Table 1.

Tipologia	n. fasi successive di progetti in corso	nuovi progetti
PNRM	38	21
EDA	0	17
Accordi Quadro	7	3
Centri di <i>Test</i>	4	6
BI-MULTILATERALI	6	7

Table 1 - Distribution of mandates carried out in 2024.

BREAKDOWN OF NATIONAL FUNDING BY CAPABILITY/TECHNOLOGY AREAS

The annual breakdown of national funding by capability/technology areas may vary based on operational priorities expressed within the Defense sector. The national projects for 2024 were selected based on the criteria established in the Minister of Defense's guidelines and updated by the Chief of Defense Staff, prioritizing project proposals relevant to the following application/technology clusters:

- C2 and Multi-Domain Situation Awareness: solutions capable of receiving, fusing, and representing in an integrated manner data from military sensors and systems belonging to the five Operational Domains (land, maritime, air, cyber, and space), Intelligence, Surveillance & Reconnaissance (ISR)
- Space Technologies: asset defense, Military Satellite Communications (MILSATCOM), Earth Observation, access to space, Space Domain Awareness (SDA), In-Orbit Servicing, Electromagnetic Spectrum Surveillance, stratospheric platforms
- Cyber Technologies: solutions for achieving awareness, defense, and attack capabilities in the cyber domain
- Protecting and enhancing soldier capabilities: human enhancement, awareness, defense and offense, reducing the negative effects of illnesses
- Autonomous Systems: technologies for the development and countering of Robotic Autonomous Systems, Unmanned Systems (UxV)
- Artificial Intelligence solutions: big data management and standardization of heterogeneous data (e.g., sensors, systems, and databases), complementary automation of remotely guided systems in non-permissive EM environments, swarm intelligence, precision targeting
- Countering "emerging" threats: directed energy weapons (including offensive capability development), weapons capable of ensuring access to areas protected by Anti-Access/Area Denial (A2/AD) or counter-A2/AD systems, cyber activities combined with electronic warfare (Cyber Electromagnetic Activities), hypersonic weapons
- Underwater: technologies for controlling the underwater dimension and for the operational effectiveness of the vehicles and devices operating there

- Urban warfare: technologies for controlling urban territory and for the operational effectiveness operational nature of the military vehicles and devices operating there
- Sustainability, security, and energy resilience: solutions for reducing the logistical and environmental footprint, safety, and energy efficiency of military infrastructure and assets (smart buildings, Nearzero Energy Buildings, field structures, biofuels and hybrid propulsion, storage, renewable energy sources for the military, energy management systems, and diversification of supply systems)
- Biotechnologies (Bioinformatics, Biosensors,

and Bioelectronics), smart materials and nanotechnologies, strengthening and developing CBRN defense capabilities

The identification of priority clusters has enabled more effective and efficient planning and management of resources, directing technological research activities toward achieving objectives consistent with the capacity needs and current priorities of the Armed Forces, and minimizing the fragmentation of technological sectors and the dispersion of resources across multiple and diverse activities, not all of which are specifically aimed at filling the capacity gaps identified at the operational level.

Area Tecnologica (<i>cluster</i>)	% finanziamento	Numero progetti
C2 e Multi-Domain situation awareness	9,5%	2
Tecnologie spaziali	33,3%	7
Tecnologia <i>cyber</i>	4,8%	1
Protezione e potenziamento capacità del soldato	9,5%	2
Sistemi Autonomi	4,8%	1
Soluzioni di Intelligenza Artificiale	4,8%	1
Contrasto minacce “emergenti”	9,5%	2
<i>Underwater</i>	14,3%	3
<i>Urban warfare</i>	0,0%	0
Sostenibilità, sicurezza e resilienza energetica	4,8%	1
Biotechnologie	4,8%	1
TOTALE	100%	21

Table 2 - Distribution of new national projects launched in 2024 with respect to the priority capability/technological clusters indicated by the Chief of Defence Staff.



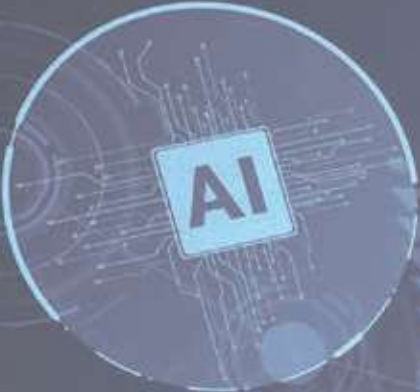
Figure 1 - Distribution of new national projects launched in 2024 with respect to the priority capability/technological clusters indicated by the Chief of Defence Staff.





ABBREVIATIONS AND ACRONYMS





ABBREVIATIONS AND ACRONYMS

2-MF	Multi-Functional Modular Frame
AD	Amministrazione Difesa
AES	Advanced Encryption Standard
ALW	Airborne platform effects on laser systems and warning sensors
AODV	Ad Hoc On-Demand Distance Vector
AU	Actuation Unit
BEE DDS	Implementazione Leonardo dello standard DDS
BER	Bit Error Rate
BFN	Beam-Forming Network
BLOS	Behind Line Of Sight
C2	Comando & Controllo
CDMA	Code Division Multiple Access
C4ISTAR	Command, Control, Communications, Targeting Acquisition and Reconnaissance
CIRA	Centro Italiano Ricerche Aerospaziali
CPA	Sistema Cooperativo basato su Percezione Aptica
COFDM	Coded Orthogonal Frequency Division Multiplexing
CMC	Materiale Composito a Matrice Ceramica
C/SiC	Composito con matrice di SiC rinforzato con fibre di Carbonio
COTS	Commercial Off-the-Shelf
CSM	Communication Spectrum Monitoring
CU	Control Unit
DIRCM	Directed Infrared Countermeasure
DDS	Data Distribution Service
DF	Direction Finding
DM	Directional Modulation (Modulazione Direzionale)
DT	Dimostratore Tecnologico
DVB-T	Digital Video Broadcasting-Terrestrial
EMI	ElectroMagnetic Interference
ESM	Electronic Support Measures
EFT	Electronic Functional Tray
ETSI	European Telecommunication Standards Institute
ELINT	Electronic INTelligence
EM	Engineering Model
E2E	End-to-End

EGSE	Electrical Ground Support Equipment
EDA	European Defence Agency
ENIVD	(European Network for Diagnostics of “Imported” Viral Diseases)
EOT	Energy on Target
FM	Flywheel motor
GHIBLI	Galleria la plasma da due MW presso il CIRA
GUI	Graphical User Interface
GFT	Geometric Functional Tray
GIM	Gimbal motor
GIS	Geographic Information System
GPS	Global Positioning System
GPU	Graphical Processing Unit
GEOINT	GEOspatial INTelligence
HfB2	Diboruro di Afnio
IDS	Intrusion Detection System
INS	Inertial Navigation System
ISR	Intelligence Surveillance and Reconnaissance
It-MoD	Italian Ministry of Defense
IMINT	Image INTelligence
ISL	Inter Satellite Link
IR	Infrarosso
J/S	Jammer-to-Signal ratio
LEO	Low Earth Orbit
LC	Load Case
LT CES	Communication Electronic Support Measures
LICOLA	Low Interceptable Communication Link Antennas
MCMG	Mini Control Momentum Gyroscope Assembly
MAC	Medium Access Control
MALE	Medium Altitude Long Endurance
MANET	Mobile Ad-hoc Networks
MCS	Mission Control System
MS-DEP	Multi-Sensor Data Exploitation Platform
MWS	Missile Warning System
NEC	Network Enabled Capability
NCS	Network Control System
OBL	Optical Break Lock
OMG	Object Management Group

ABBREVIATIONS AND ACRONYMS

OTW	Other Than War
OBP	On-Board Processing
PCR	(Polymerase Chain Reaction)
POC	Posto Operatore Centralizzato
P/F	Piattaforma
P/L	Payload
POI	Point Of Interest
RMSE	Root Mean Square Error
RIFON	Rete Interforze in Fibra Ottica Nazionale
RPAS	Remotely Piloted Air System
RSV	Reparto Sperimentale di Volo
SATCOM	Satellite Communication
S/C	Spacecraft
SIMP	Solid Isotropic Material with Penalisation
SHF	Super High Frequency
SIC	Carburo di Silicio
SICRAL	Sistema Italiano per Comunicazioni Riservate ed Allarmi
SiC/SiC	Composito con matrice di SIC rinforzato con fibre di SIC
SOTA	State Of The Art
TA	Technical Arrangement
TAPR	Aeromobile a Pilotaggio Remoto
TAS-I	Thales Alenia Space Italia
TAKS	Topology Authenticated Key Scheme
TRL	Technology Readiness LevelDMA
TRM	Traffic Resource Manager
TRM-DB	TRM Data Base
UV	Ultra Violetto
UHF	Ultra High Frequency
VANET	Vehicular Ad-Hoc Networks
VFT	Volumetric Functional Tray
VHF	Very High Frequency
WP	Work Package
WIFI	Wireless Fidelity
WIDS	WPM-based Intrusion Detection System
WSN	Wireless Sensor Network
WHO	(World Health Organization-Organizzazione Mondiale della Sanità)
ZrB2	Diborure di Zirconio

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