EUROPEAN
DEFENCE
AGENCY

EDA RESEARCH, TECHNOLOGY AND INNOVATION

PAPERS AWARD 2024

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FOREWORD

"*Si vis pacem, para bellum*" – If you want peace, prepare for a war. A future war.

Dear Reader,

Modern security and defence challenges confronting Europe today are increasingly complex and multi-vectoral, necessitating innovative approaches and solutions. As the security landscape in Europe evolves in complexity and unpredictability, the need for innovative and forward-looking defence solutions has never been more urgent. Emerging technological threats challenge traditional approaches to safeguarding our societies. To address these multifaceted challenges, it is crucial to identify and nurture novel defence concepts that can anticipate and outpace potential adversaries. This requires collaboration, vision, and a commitment to cutting-edge technological advancement at all levels – starting with innovation at the grassroots and culminating in large-scale implementation across the defence sector. Facing limited resources, it is also important to prioritize investment in the research and development of cutting-edge defence technologies. Only by doing so we can effectively address future challenges and safeguard the security of EU's citizens.

At the European level, fostering innovation is not only a necessity but a strategic priority. By cultivating an environment that encourages start-ups and small businesses to develop disruptive defence solutions, we open the door to fresh perspectives and game-changing technologies. The European Defence Agency has long been a driving force behind these efforts, identifying and supporting non-traditional actors, including individual innovators, research communities, start-ups and SMEs, that bring innovative technologies to the forefront of the defence community. Initiatives undertaken by the Hub for EU Defence Innovation, such as EDA Research, Technology, and Innovation Papers Awards, and the Defence Innovation Prizes have paved the way for them to contribute directly to the development of defence capabilities that will shape the future of European security. This publication highlights the importance of nurturing innovative defence concepts and showcases the contributions made by early career researchers to technological progress and war art development. Through collaboration, support for research, and a shared vision for future defence needs, we will continue to push the boundaries of what is possible, ensuring that European defence remains robust, adaptable, and ahead of the curve.

Yet, innovation does not end with concept development. Equally important is the commercialization – a process that is usually driven by large industries. These key players have the expertise, resources, and networks required to scale up cutting-edge solutions, ensuring they reach operational readiness and provide real-world benefits for European armed forces. By bridging the gap between start-ups, research institutions, and industry giants, we create a comprehensive innovation ecosystem that accelerates the path from an idea to implementation. However, the role of deep science at academia and inventiveness being a domain of the deep-tech start-ups and their ability to harness emerging technologies, such as artificial intelligence, advanced robotics, and quantum computing, can no longer be overlooked. Their agility in responding to new challenges, coupled with the vast experience of the larger defence industry in scaling these solutions, holds the potential to revolutionize defence capabilities across the EU. By leveraging this synergy, we can address future defence challenges with unmatched effectiveness, ensuring Europe remains secure in an increasingly volatile global environment.

Together, let us continue to inspire and drive innovation for a safer future.

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EUROPEAN DEFENCE INNOVATION: EDA'S ROLE IN "TECHNOLOGY PUSH" CAPABILITY DEVELOPMENT

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Abstract

The European Defence Agency is a cornerstone of the EU's efforts to enhance defence ecosystem stakeholders' collaboration, foster innovation, boost industrialization, and build durable critical military capabilities. By promoting joint initiatives in a coordinated manner, the EDA plays a key role in driving technological advancements and ensuring that Europe is prepared to address evolving security threats. With a strong focus on defence innovation, the EDA is helping the EU to build the capabilities it needs for the future, ensuring that the "old continent" remains a relevant player in the global security and defence architecture. However, achieving this vision requires the continued commitment of member states to deepen European defence environment integration.

Keywords

Defence and security collaboration, Defence capability, Technological innovation, Emerging and disruptive technologies, Future battlefield model.

1. COOPERATION IS THE KEY

The European Defence Agency, as an important intergovernmental EU's institution, plays a pivotal role in advancing the European Union's defence policy by fostering collaboration among member states, enhancing defence capabilities, and driving innovation [1]. As Europe faces a rapidly evolving security landscape, characterised by an old fashion, full-scale war threat, but also new challenges below the threshold of war (a so-called hybrid warfare), such as cyberattacks, critical infrastructure sabotages, public opinion manipulation utilizing new media and communication means, and overall regional and MSs' internal instability ignition acts, the EDA has become an essential platform for coordinating EU member states' defence efforts.

Historically, defence policies within the EU have been characterised by fragmentation, with individual member states pursuing separate and sometimes overlapping military projects. The EDA works to mitigate this fragmentation by encouraging cooperation, pooling resources, and ensuring that defence initiatives are complementary rather than duplicative. Its mandate encompasses defence collaboration in terms of defence capabilities development, join defence research, and innovation, as well as industry capacity building [2], which together contribute to ensuring that Europe can protect its political and economic interests, among others by maintaining global competitiveness in defence technologies.

1.1. ENHANCING DEFENCE CAPABILITIES BUILDING

Building defence capabilities is a core component of the EDA's mission. The agency focuses on strengthening the EU's ability to collectively respond to security threats by fostering the development and deployment of new military assets. It plays an instrumental role in facilitating joint projects aimed at filling strategic capability gaps identified at both the national and EU levels.

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One of the key frameworks in this regard is the Capability Development Plan (CDP), which sets out priorities for the development of defence capabilities across the EU [3]. The CDP helps to guide national investments in defence and ensures that these investments align with EU strategic objectives. This ensures coherence between national defence policies and broader EU goals, avoiding unnecessary redundancies and fostering the joint development of critical components.

2023 EU Capability Development Priorities

EUROPEAN DEFENCE AGENCY

LAND
- Ground Combat Capabilities
- Land Based Precision Engagement
- Future Soldier Systems

AIR
- Air Combat Platforms & Weapons
- Airborne Command & Inform Capabilities
- Integrated Air & Missile Defence
- Air Transport

MARITIME
- Naval Combat & Maritime Interdiction
- Underwater & Seabed Warfare
- Maritime Domain Awareness

SPACE
- Space Operations
- Space Services

CYBER
- Full Spectrum Cyber Defence Operations Capabilities
- Cyber Warfare Advantage & Readiness

STRATEGIC ENABLERS & FORCE MULTIPLIERS
- Electro Magnetic Spectrum Operations (EMSO) Dominance
- Persistent & Resilient C4ISTAR
- Military Mobility
- Critical Infrastructure Protection & Energy Security
- Sustainable and Agile Logistics
- Medical Support
- Chemical, Biological, Radiological & Nuclear (CBRN) Defence
- Cohesive & Well-Trained Militaries

Figure 1. CDP priority domains

By promoting technical and operational interoperability, as well as further joint military equipment development and procurement the Agency strengthens the EU defence and security, while many further mentioned success stories are an undisputed proof of a meaning if open collaboration.

The EDA serves as a coordination hub for defence cooperation, providing a platform for member states to align their defence planning and common capability requirements. Through a Coordinated Annual Review on Defence (CARD) [4], utilizing outcomes of all the three operational agency’s directorates analysis, as well as a voluntary MSs contribution, the agency identifies common operational, technical and industrial gaps and collaborative synergies across national defence plans, helping member states cooperate more effectively within joint projects.

The EDA plays also a pivotal role in the development of European industrial capacity in arms production while lastly also in directly facilitating joint procurement of military equipment and war materials. Its efforts are central to enhancing the strategic autonomy of the European Union and addressing the fragmented nature of the European defence market. Recently, this role has gained heightened importance due to the war in Ukraine, which has underscored the necessity for more coordinated and efficient defence mechanisms, in both peace and war times.

Furthermore, what truly makes a difference, the EDA's efforts have enabled smaller EU states to participate in defence projects they might otherwise lack the capacity to undertake. By pooling resources, smaller nations can access advanced defence technologies and systems, enhancing their military capabilities while also contributing to the collective security of the EU.

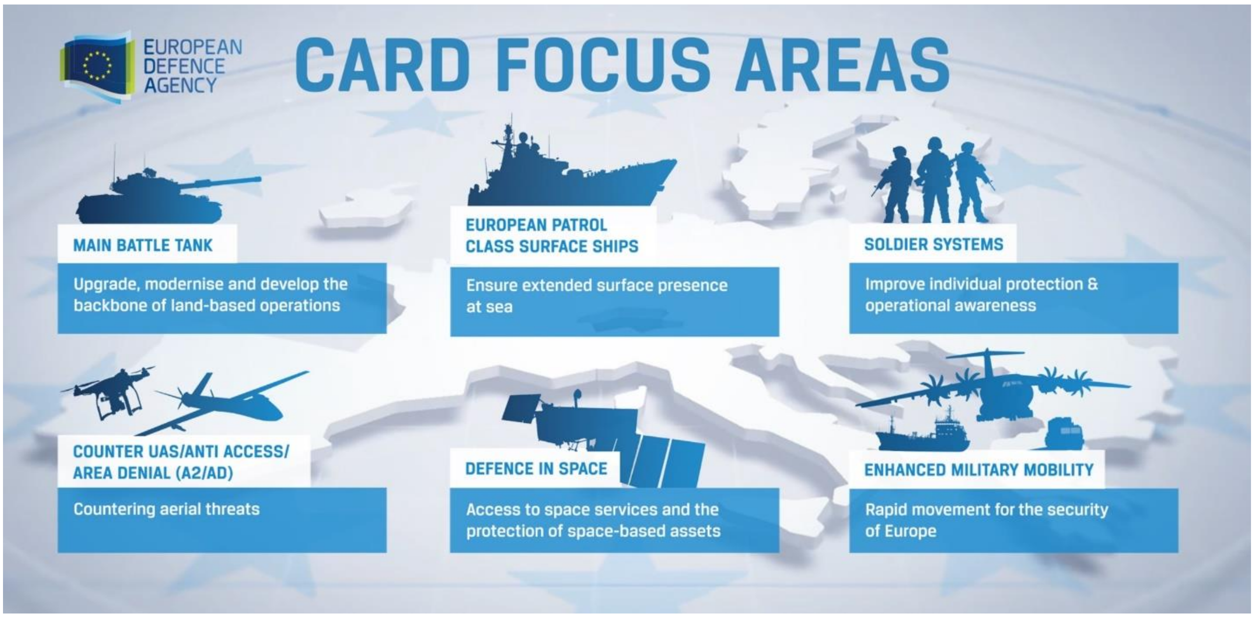


Figure 2. CARD Focus areas

As an executive work strand, the EDA manages Permanent Structured Cooperation (PESCO) between member states covering all 5 operational domains [5], including cyberspace and informational dominance, supporting both training facilities and military exercises, as well as true combat capabilities, benefitting from this shared approach, avoiding inefficiencies and ensuring that resources are used optimally. Through these initiatives the EDA also promotes the standardisation and interoperability of military systems across member states, a crucial factor in ensuring that European forces can operate together effectively in joint missions. Some of the PESCO projects ignite cooperation within European Defence Fund Framework, and finally even end up with collaborative development and procurement projects, e.g. under OCCAR management umbrella, like MALE Eurodrone, Eurocopter Tiger MkIII or European Secure Software Defined Radio.

1.2. SUPPORTING INDUSTRIAL ENGAGEMENT

Another one of the key mandates of the EDA is to strengthen the European Defence Technological and Industrial Base (EDTIB) to leverage economies of scale in the production of armaments [6]. Through its work, the EDA seeks to enhance the competitiveness and innovativeness of the EDTIB, which includes not only large defence contractors but also small and medium-sized enterprises (SMEs) that are critical for innovation and specialized production. By promoting cross-border collaboration, starting from a deepened research project, the agency encourages the joint development of advanced military technologies and systems and the pooling of industrial resources. This approach is crucial in an era where modern warfare increasingly relies on cutting-edge technologies such as cyber defence, artificial intelligence, unmanned systems, and precision-guided munitions.

The joint procurement of military equipment is an important EDA work strand contributing to strengthening EDTiB. Historically, European countries have pursued independent procurement strategies, leading to fragmentation and inefficiencies in a best-case scenario, while often placing orders outside of EU territory. Streamlining procurement processes and ensuring the coordination of national defence plans not only reduces costs through bulk purchasing but also enhances interoperability between European forces, which is crucial for coordinated military operations.

The war in Ukraine has clearly revealed effects of underinvestment in the European defence industry's production capacity, as well as shortages in materiel. Thus, exposed the need for more resilient and flexible supply chains within the EU's economic zone. The EDA responds to that need by implementing Key Strategic Activities (KSA) [7] and corresponding Priority Implementation Roadmaps (PIR), based on thorough analyses of EU defence industrial and technological capacities to identify critical areas that can strengthen EU strategic autonomy. The initiative aligns with the New Industrial Strategy for Europe, which promotes EU sovereignty in industrial sectors, including defence and space.

Paramount goals of KSA include raising awareness and aligning funding opportunities from EU and national sources, like the European Defence Fund (EDF), European Regional Development Fund under the European Structural and Investment Funds, to support targeted industrial and technological areas, especially where dependencies on non-EU entities may limit EU defence autonomy. This approach fosters collaboration among Member States on defence priorities and strengthens the EDTIB, with a focus on small and medium enterprises and critical materials. These reports are dynamic, continually updated to reflect changes in technology, industry, and EU defence priorities.

As an example, by implementation of PIRs, as well as facilitating joint, concentrated procurement efforts, in this case to replenish the ammunition stockpiles of EU member states, many of which have been depleted as they continue to send military aid to Ukraine, EDA supports the European Commission in implementing Act in support of ammunition production. This highlights the importance of coordinated procurement strategies to ensure that Europe becomes and further remains capable to meet the needs of a potential future full-scale war, as industry rather responds to market needs than keeps production capacity just in case, in case of possible war and largely increased consumption, which has not been the case for decades.

2. DEFENCE RESEARCH, TECHNOLOGY AND INNOVATION – A STRATEGIC PRIORITY

Defence innovation is increasingly recognised as vital for maintaining Europe's security and defence autonomy. The rise of new and disruptive technologies, such as artificial intelligence (AI), robotics, quantum computing, and hypersonic weapons, is transforming the nature of warfare. To stay ahead in this rapidly changing environment, the EDA has placed significant emphasis on promoting defence innovation and addressing the future capability needs by relevant research.

By promoting collaboration between defence industries, research institutions, and national governments, the EDA helps drive technological breakthroughs that enhance Europe's defence capabilities. The agency plays a key role in facilitating partnerships between public and private sectors, and between civilian and military R&D, ensuring that innovative ideas are translated into practical defence applications. Moreover, the EDA's focus on dual-use technologies—those that have both military and civilian applications – further amplifies the impact of defence innovation on the broader EU economy.

Additionally, the EDA supports the development of emerging technologies through its participation in external international collaborative R&D initiatives, such as the European Defence Research and Innovation Network (EDRIN) and the Preparatory Action on Defence Research (PADR)/European Defence Fund. These programmes ensure that Europe remains at the forefront of technological advancements that can reshape the future of defence.

2.1. EUROPEAN DEFENCE RESEARCH AGENDA

Primarily however, the European Defence Agency plays a crucial role in fostering cooperation and coordination among European Union members and associated countries within the Research, Technology and Innovation Directorate's CapTechs (Capability Technology Groups) which drive the future of European defence capabilities and research strategies [8], maintaining Overarching Strategic Research Agenda (OSRA). Each CapTech group focuses on a specific domain (operational – land, air, space, maritime, cyberspace, as well as various relevant technical scope), addressing the unique technological challenges within that field.

OSRA is a strategic framework designed to align defence research and technology development with the long-term capability needs of EU member states [9]. It serves as a high-level guide that identifies key research areas, ensures coherence across different initiatives, and promotes synergies between civilian and military research, ensuring that research efforts within the EDA and across EU member states align with the capability development goals of the Common Security and Defence Policy (CSDP), while maximizing resource efficiency and innovation potential.

Figure 3. Exemplary critical technological enabler domains

CapTechs, among others, contribute also to:

- Collaborative R&D – facilitating cross-border collaboration on defence technology projects by pooling expertise, resources, and funding.
- Technology Watch & Foresight – addressing such questions as what worldwide scientific developments could impact defence and security in the future and how to ensure awareness to emerging scientific developments, as well as how to exploit new technology and thinking to overcome our current challenges?
- Develop plans and programmes for technology development (e.g. Action Plan on Autonomous Systems).

2.2. HEDI TO FOSTER INNOVATION FROM AN IDEA TO IMPLEMENTATION

On May 17, 2022, EU Defence Ministers approved the creation of the Hub for EU Defence Innovation (HEDI) as a follow-on action from the Strategic Compass for Security and Defence [10], designed to enhance already in place and initiate new cross-directorate innovation efforts within the European Defence Agency. HEDI acts as a platform to promote and facilitate collaboration on defence innovation among EU member states. The hub's activities align with EU priorities for the Capability Development Plan and the Overarching Strategic Research Agenda, complementing also European Commission initiatives and NATO's innovation activities. HEDI focuses on three key areas: identifying innovative ideas and innovators, developing and implementing these ideas, finally increasing innovation climate within the defence community.

The initial portfolio of the Hub for EU Defence Innovation (HEDI) is organized into six key activity clusters [11]:

Common Picture: HEDI contributes to building a comprehensive overview of defence innovation, covering best practices, methodologies, lessons learnt, as well as the status and perspectives of projects related to EDTs across EU and worldwide. Defence innovation experts from member states participate in a work of an innovation community (European Defence Innovation Network – EDIN) to exchange insights, helping to professionalize and scale up innovation efforts across Europe.

European Defence Innovation Days. HEDI organizes a biannual event to showcase hi-tech project outcomes, raise awareness of the European defence innovation ecosystem, and connect various stakeholders. These shows include conferences, exhibitions, discussion panel with a theme selected by the Hub. The exhibition space is dedicated cooperative and national defence innovation projects. Based on previous excellent experience, next year, for the first time outside of Brussels (Krakow, Poland) the European Defence Innovation Days (EDID) will embrace also an additional attractive agenda item – a defence higher education robotic teams makeathon aimed at bringing technical universities closer to defence industry and end-users.

EDA Innovation Prizes. These prizes aim to gather innovative ideas and solutions at various stages of technological readiness to address identified gaps. Prize winners receive seed funding to develop their concepts into proof-of-concepts or demonstrators. Last year HEDI expanded this initiative by increasing the number of prizes and the areas they cover, accelerating the integration of innovation into defence capabilities. The prizes target early-stage innovation, encouraging participation from diverse actors, including academic society, RTOs, start-ups and SMEs, especially those non-traditional.

Innovation Challenges. Challenges and hackathons, which are rapid development cycles from a proof-of-principle to a minimum viable product, have been introduced to attract non-traditional defence players, but especially scientific communities to contribute to defence hi-tech chain of supplies. HEDI, in collaboration with EDIN, identifies innovations needs to cover urgent capability gaps highlighted by member states, organizes competitions and oversees field experimentation of selected solutions. The first campaign will be managed during European Defence Innovation Days in 2025 and embrace land autonomous platforms.

Proof-of-Concept. Leveraging EDA's flexible contractual framework and various funding streams, HEDI advances the development of the most promising technologies, prioritizing those that show the most potential and support from end-users, providing additional funding from EDA's operational budget to competitively chosen best consortia to run a sprint of technology development.

Uptake of Innovation. To ensure coordinated integration of innovations into defence capabilities, HEDI has explored and developed a multinational Concept, Development, and Experimentation, and Concurrent Design campaign tools, to address the most urgent defence capability needs of participating MSs. Next year, as a pilot project, there will be executed the first EU Defence Innovation Operational Experimentation Campaign on Autonomous Systems for Cross-domain Logistics.

Whilst HEDI is still under a ramp-up phase, growing in terms of manpower and experience as a co-operation platform, it also works together with EU Member States and other relevant EU institutions on future structure and portfolio of services, to better align with modern, agile innovation management methodologies, streamlined with rapidly changing EU's and global defence ecosystem.

3. EDA RTI PAPERS AWARD 2024 OVERVIEW

While HEDI's services include the launch of various contests, as a holistic, systemic approach of military innovations, the EDA Research, Technology, and Innovation Papers Award's main target is to promote early career researchers, primarily (but not exclusively) from a scientific community. The goal of the award is to introduce their work to the traditional defence community. Therefore, RTI Papers Award contest aims to bring new expertise closer to end-users and the industry creating a room for further, closer R&T cooperation.

In contrast to the EDA Defence Innovation Prizes, where the topics are more focused and limited in scope, the EDA RTI Papers Award remains open, being titled "Innovative technologies, processes, and applications for enhanced future defence capabilities". As innovation does not live long. The expectation from this call for papers is to collect a pool of new ideas and concepts to unconventionally fill current or future capability gaps, as well as broaden the horizons on possible technological progress directions and war art potential paths of change. Following the success of the first edition, the European Defence Agency launched this year the second one and plans to launch it on a yearly basis. Participants to this call for papers are always requested to think "out-of-the-box", as the collected material valuably contributes also to other EDA's activities, such as Technology Watch and Strategic Foresight or Overarching Strategic Research Agenda.

While the first edition of the RTI Paper Awards was awarded during the European Defence Innovation Days 2023, and the conference is organized on the biannual basis, this year's EDA Defence Research, Technology, and Innovation Papers Award awarding ceremony took place at the EUROSATORY 2024 exhibition, on 19th of June.

The submitted papers were assessed by an Evaluation Committee composed of various EDA experts, both operational and technical, as well as with broad experience in defence business, against several criteria, such as:

- technological innovativeness and disruptiveness and scientific value;
- potential impact on future military application(s) (e.g., 2035 onwards, all CDP priorities can be addressed);
- economic value of the proposal in terms of battlefield saturation, industrial added value.

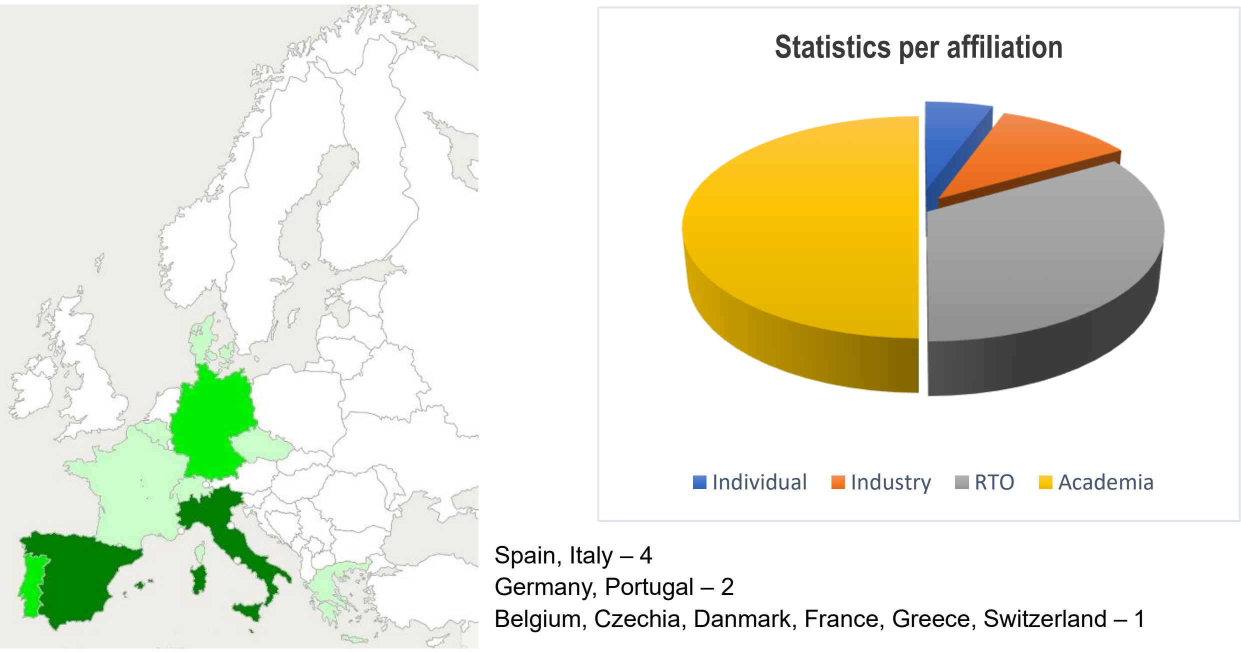
Table 1. List of articles

No.	Title	Overview	Authors
1.	Military applications of biomass-fuelled engines and their impact on the performance of Armed Forces	The paper presents a well-researched exploration of biomass-fuelled engines as an alternative to petroleum-based fuels for military applications, highlighting some potential benefits in performance, safety, and energy independence.	G. Suanes, D. Bolonio, J. I. Yenes and A. Cantero
2.	European Hypersonic Space Defender	The paper proposes a compilation of three different modules that are to be further developed within R&D projects: NG fuselage (Eurohunter) European Solar Space plane, the space Quantum propellant, and Quantum Noise Teleportation (communication).	J. J. Navlet
3.	Teledetection of Land Objects System (TelLOS)	The paper proposes a multispectral detection system (TelLOS) expressing a need of a multiple sensor operating in all wavebands: up to mm radio spectrum waves, as well as THz optical bands, emphasizing necessity of adapting configurations and further data fusion for standoff weaponry target detection.	A. L. Jiménez
4.	AI-generated threats to maritime navigation using deceptive ISAR images	The proposed research paper proposes an innovative technology approach to an existing cybersecurity issue – emerging threats by sophisticated attacks within the signal processing chain via the use of newly generated fake ISAR images.	G. Meucci, F. Mancuso and A. Cantelli-Forti
5.	Enhancing military helicopter operation: a study on ballistic impact damage detection	The paper describes a method that could contribute positively to the field of military aviation, presenting a well-executed study on integrating AI for damage detection. The integration of the NARX model into existing helicopter systems could represent a step improvement in enhancing safety and operational efficiency.	V. Panagiotopoulou, E. Petriconi, M. Giglio and C. Sbarufatti
6.	A new covert era in maritime surveillance and reconnaissance	The paper provides a clear solution proposal on using a satellite illuminator of opportunity for passive radars when no commercial communication and broadcast services provided exists, like in a scenario open sea.	I. Pisciottano, D. Cristallini, F. Santi and D. Pastina
7.	CROWS: Common Resilient Operational Weather System	The paper turns around a methodology describing a solution for tailored AI hardened meteo data analytics, at all stages of data collection, to a more precise and localized approach.	D. Sládek
8.	Towards small object detection in space: photonic integrated quantum illumination	The paper refers to a quantum entanglement in radar and cameras in target detection for space application e.g. small debris and satellite at LEO orbits detection and tracking with sub-THz waves.	I. Carnoto Amat, J. César Cuello, P. Fajardo1, L. E. García Muñoz, R. M. Pulido Puerto and F. J. Morales Comalat

9.	SpaceGuard: How space law enforcement can enhance space security through comprehensive monitoring and response to theats	The paper presents highly innovative and disruptive ideas in the area of SSA and space-protection to autonomously inspect unknown and uncooperative Resident Space Objects. By a capability perspective, this technology could facilitate the Space Operations, in particular the force protection and the resilience of space assets, fully addressing the congested and contested military domain that Space is already representing.	M. Maestrini, N. Faraco, M. A. De Luca and P. Di Lizia
10.	3D radar imaging for non-cooperative target recognition	The paper presents the results obtained in an R&D project done in partnership at EU-level. This article addresses the new way of looking at using radar for NCTR, especially overcoming the challenge of mapping geometry into the 2D ISAR image.	E. Giusti, S. Ghio, M. Martorella , P. Samczynski, J. Drozdowicz, M. K. Baczyk, M. Wielgo, K. Stasiak, J. Julczyk, M. Ciesielski, M. Soszka, R. Mularzuk, F. Principi, L. Banchi, D. Staglianò and S. Lischi
11.	SPINAR: Spin-based artificial neural network for embedded rf processing	The paper covers a very interesting topic of close to real time extreme wideband signal processing based on AI spinar hardware, with various radioelectronic applications, especially radar surveillance and electronic warfare. Moreover, low power consumption makes it very promising in aerial and space domains, which are crucial for modern battlefield EW	A. De Riz, P. Bortolotti, J. Grollier and F. A. Mizrahi
12.	Are the European chips act, critical raw materials act, economic security strategy, and global gateway not enough? – EU defence sector critical raw material supply chain vulnerability solutions from Japan	The paper embraces a political-economic study on EU's critical RM and components on third countries, with a special focus on China, based on an example of Japan.	D. Seiler
13.	Intelligent swarm coordination in a coms-denied surveillance landscape	The paper provides a simplified study on the coordination of UAV swarms in communication-denied environments, a critical aspect of mosaic warfare. The paper relies on a case of map exploration. The study focuses on decentralized decision-making processes and their effectiveness in maintaining operational efficiency under varying levels of communication denial.	A. E. Vasegaard, A. K. Larsen, C. B. Pedersen and M. B. Ladefoged
14.	Simultaneous lightwave information and power transfer for non-terrestrial networks enabled situational awareness	The paper emphasizes mainly the importance of SLIPT for UAV and CubSat for better situation awareness, and concurrently – laser beam power transfer.	P. D. Diamantoulakis, S. A. Tegos, G. K. Karagiannidis, L. Athanasekos and D. Nodaros

15.	Dual-use technologies and decentralized manufacturing: An opportunity to revolutionize European defence innovation	The paper covers an interesting Swiss initiative, to some extend inspired Ukrainian experience from the current war in terms of drone production and civilian assets adaptation to war conditions in field workshops utilizing various 3D printing technologies, taking advantage of simulations and military exercises to produce fit for purpose solutions and inspiring evolution of TTPs.	R. Chandra and A. Geller
16.	Autonomous cyber defence agents using DRL and LLMs to protect critical infrastructure networks	The paper covers a very interesting topic of newest AI methods hardened semi-autonomous cyber defence, taking advantage of deep reinforcement learning and large language model for better man-machine teaming.	J. F. Loevenich, E. Adler and R. R. F. Lopes

High quality of the submitted papers covering various important fields, such as (among others) cybersecurity, artificial intelligence, informational superiority, autonomous systems, space dominance, 3D printing proves that the initiative brings valuable expertise to the defence community, with new operational concepts for innovative technologies utilization, but not forgetting about such important topics as green defence, and reliability of chains of supplies, addressing climate changes and geopolitical issues.



Spain, Italy – 4
Germany, Portugal – 2
Belgium, Czechia, Danmark, France, Greece, Switzerland – 1

Figure 4. Geographical coverage and affiliation of the papers' authors

Although the number of received submissions remains good, similar to the first edition, the above figures show, that there still are blind spots on the map. This means that the contest should be better advertised to reach out new communities and have a better geographical coverage. As optimistic, it should be considered participation of Danish innovators in HEDI activities, after joining EDA in March 2023. The contest addressed to early career researchers reaches its target – Academia and RTOs, however, there is still a big room for improvement in terms of bringing additional actors to the table, as most of the proposals come from organizations with experience in international co-operation under EDA's umbrella. Except of EDA's role, engagement of national defence innovation ecosystems' managers is crucial in this term.

4. CHALLENGES IN EUROPEAN DEFENCE COOPERATION

European defence collaboration faces several challenges that stem from the diversity of defence policies, national interests, and market fragmentation among EU member states. EU member states, those from the eastern flank vs south-western, with Germany, Austria or BENELUX in the middle of the scene, have even completely different security concerns, leading to a lack of consensus on which capabilities should be prioritized for collective development. As defence R&D and procurement spendings varied significantly among member states, this led to overlapping projects, duplication of efforts and loosing synergy effect across Europe, with its second economics in the world. And what does not fill with optimism is even more, overall European investment in defence technological innovation lags global competitors like the US and China, which makes keeping the technological and operational edge even harder. This requires developing and maintaining a clear, common collective vision for European security architecture, aligned with the EU's Strategic Compass.

And this becomes even more crucial now, especially in an era of potential American strategic pivot to Ino-Pacific. As Mario Draghi – former Italian prime minister and European Central Bank President writes in his report on European competitiveness, enhanced cooperation among EU member states will enable a more effective response to potential threats from nations like Russia and China, increasing its independence from US at the same time [12]. Therefore, Draghi highlights the need for a comprehensive policy on defence research, aimed at maintaining Europe's competitive edge in critical technologies, such as cybersecurity means and robust digital defence to safeguard EU infrastructure and forces, in times below the threshold and beyond.

Establishing stronger coordination mechanisms through the European Defence Agency and its initiatives like OSRA/CDP/PESCO/KSA and CARD to ensure alignment of national R&D and Implementation agendas with European defence priorities can allow EU to overcome these challenges. Joint R&D programmes and projects, both "high altitude long endurance" programs as well as short concept development and experimentation campaigns that focus on shared technology priorities, towards further joint military equipment procurement, funded through instruments like EDA cat. A or B or within the European Defence Fund [13], can bring a significant technological and capability advancement. But also, what may be even more important, strengthens cross-border ties and builds mutual trust between MSs. Each successful project certainly encourages member states to leverage join EU funding mechanisms to support more and more collaborative defence spendings and ultimately meet NATO and EU targets (at least 2% of GDP, of which 20% for new equipment procurement and 2% of R&D – at least). One of the ways to address this challenge is to foster Public-Private Partnerships to encourage more private sector participation in defence R&D, pooling public resources with private innovation.

There are diagnosed significant deficiencies in critical defence areas like space capabilities, autonomous systems, where European states lag other global powers. Maybe not a remedy for everything but one of effective policies can be leveraging civil-military synergies in dual-use technologies, such as e.g. artificial intelligence, space, and quantum technologies, cloud vs edge computing, 5/6G communication to bridge capability gaps. Use the European Defence Fund work programme and a European Defence Innovation Scheme, as part of a comprehensive approach to EU's ecosystem building, supported by NATO's Defence Innovation Accelerator for the North Atlantic, to focus on filling key capability gaps, especially in emerging technologies, should constitute a friendly environment for European defence innovation to fast-track promising technologies into operational capabilities.

And yes. The European defence market is fragmented, with national economic interests, many small and medium-sized enterprises operating in isolation, making it difficult to compete with larger, more integrated defence industries operating globally. It requires more and more incentives for collaboration among defence companies, particularly SMEs, across different member states, encouraging the creation of cross-border defence supply chains, promoting consolidation to foster more integrated, competitive, and scalable European defence concerns, capable of competing on the global stage.

With different systems, standards, and doctrines across European armies, interoperability is a major challenge in ensuring joint operational effectiveness. Work towards harmonizing technical standards, especially in C5ISR systems and ammunition, as well as common doctrines, tactics, technics and procedures across the EU through common military standards and joint training programs is the only way. On the other hand, differences in national export controls, defence market regulations, and protectionist policies hinder the development of a truly integrated European defence industry. The work towards a common EU export control policy to streamline arms exports and reduce regulatory bottlenecks for defence companies, but also procurement procedures, is invaluable, however, continuous efforts to establish a single market for defence in the EU must be based on respect of national ambitions and economic interests. The EDA, serving as a collaboration platform and the expertise source can answer those multiple needs.

The above mentioned is to some extent doable in a relatively short term. There is a much more challenging issue. Europe relies heavily on non-EU suppliers, particularly the US, for critical technologies (e.g., advanced microelectronics, raw materials, including energetic and rare earth metals and other minerals, chemistry and medicine materials), limiting strategic autonomy. Technological sovereignty requires investing in indigenous European defence technologies and reduce dependency on non-EU suppliers by developing strategic sectors, such as microelectronics, AI, and space systems, but also seeking for alternative supply chains for materials where EU faces large shortages.

5. CONCLUSIONS

The European Defence Agency is playing a crucial role in the EU defence and security ecosystem. By promoting innovation, cooperation, and efficiency in the defence sector, the EDA is helping to address the challenges posed by a fragmented European defence market. Its efforts are also essential in meeting the urgent needs of Ukraine, showcasing the importance of coordinated military aid and efficient supply chains. Moving forward, the EDA will remain central to the EU's goal of achieving strategic autonomy and ensuring the collective defence capability of Europe in an increasingly mutable world.

Based on past experience, to more easily overcome these challenges, the EU needs to enhance coordination and increase investment in defence research, as it seems to be easier to build trust at this stage of technology development, where scientific gals are paramount, which can further foster a more integrated defence industry. Mechanisms like the European Defence Fund (EDF), CapTechs, and OSRA are essential to aligning efforts across R&D, capability development, and industrial capacity. Additionally, building a more unified approach to procurement, standardization, and export control will help Europe develop a more competitive, efficient, and strategically autonomous defence ecosystem.

References

[1] COUNCIL DECISION (CFSP) 2015/1835 of 12 October 2015 defining the statute, seat and operational rules of the European Defence Agency

[2] EDA website: https://eda.europa.eu/what-we-do – Last accessed 23.10.2024

[3] The 2023 EU Capability Development Priorities https://eda.europa.eu/docs/default-source/eda-factsheets/cdp-factsheet---eda---14-nov-2023.pdf - Last accessed 23.10.2024

[4] Coordinated Annual Review on Defence: https://eda.europa.eu/what-we-do/EU-defence-initiatives/coordinated-annual-review-on-defence-(card) – Last accessed 07.11.2024

[5] Permanent Structured Cooperation PESCO): https://eda.europa.eu/what-we-do/EU-defence-initiatives/permanent-structured-cooperation-(PESCO) – Last accessed 07.11.2024

[6] European Defence Technology and Industrial Dependencies: https://eda.europa.eu/what-we-do/all-activities/activities-search/european-defence-technology-and-industrial-dependencies – Last accessed 08.11.2024

[7] EDA ISE Key Strategic Activities: https://eda.europa.eu/what-we-do/EU-defence-initiatives/priority-setting/key-strategic-activities - 12.05.2023

[8] EDA RTI CapTechs: https://eda.europa.eu/what-we-do/research-technology/capability-technology-areas-(captechs) – Last accessed 23.10.2024

[9] EDA Overarching Strategic Research Agenda: https://eda.europa.eu/docs/default-source/brochures/eda-osra-brochure.pdf – Last accessed 23.10.2024

[10] EU Strategic Compass for security and Defence: https://www.eeas.europa.eu/sites/default/files/documents/strategic_compass_en3_web.pdf – Last accessed 23.10.2024

[11] Hub for EU Defence Innovation https://eda.europa.eu/what-we-do/research-technology/hedi – Last accessed 23.10.2024

[12] Mario Draghi's report The future of European competitiveness – A competitiveness strategy for Europe https://commission.europa.eu/topics/strengthening-european-competitiveness/eu-competitiveness-looking-ahead_en#paragraph_47059 – Last accessed 23.10.2024

[13] European Defence Fund: https://defence-industry-space.ec.europa.eu/eu-defence-industry/european-defence-fund-edf-official-webpage-european-commission_en – Last accessed 23.10.2024

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MILITARY APPLICATIONS OF BIOMASS-FUELED ENGINES AND THEIR IMPACT ON THE PERFORMANCE OF ARMED FORCES

G. Suanes[1], D. Bolonio[2], J. I. Yenes[3] and A. Cantero[4]

Abstract

Biomass is an abundant, renewable and currently underutilized energy source. Given the need to replace petroleum-derived fuels, biomass from agricultural crops (mostly cereal straw and pruning remains) and forestry by-products should be used as fuel for internal combustion engines. Therefore, a Biomass-Fuelled Engine has been developed. To prove the feasibility of the proposal, a working prototype was manufactured from the engine of a farm tractor. The use of biomass as fuel can improve the performance of the Armed Forces. Biomass is a widespread resource that can reduce energy dependence. In addition, it can usually be obtained on the battlefield. Furthermore, the lower inflammability of biomass and its ability to absorb energy can improve vehicle safety. Finally, large civilian applications are expected to be interesting for decarbonization.

Keywords

Biomass, Alternative fuels, Oil depletion, Combustion engine, Decarbonization.

1. STATE OF THE ART

1.1. THE ENERGY DEPENDENCE OF ARMED FORCES

Today's society depends on fossil fuels. Basic activities, such as transportation and food production, depend on them. The Defence sector is no exception. The operation of the Armed Forces depends largely on the supply of fuels derived from petroleum [1]. But, petroleum resources are located in specific areas of Earth's crust [2]. A very valuable resource is concentrated on few hands. This has been a near-constant source of conflict, with the current Ukrainian war being the most recent example. Almost certainly, it can be said that if Europe had not been dependent on Russian hydrocarbons, then invasion would not have occurred. In addition, the use of fossil fuels is increasing the concentration of carbon dioxide in the Earth's atmosphere, increasing the global mean temperature, and threatening to cause harmful changes in the biosphere [3]. But the biggest problem is that fossil fuels are a finite resource. Petroleum reserves are expected to be depleted in this century [4]. For this reason, there is an urgent need to look for alternatives.

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Most European countries belong to the North Atlantic Treaty Organization (NATO). The NATO Logistics Handbook [5] established the JP-8 (F-34) fuel as a standard fuel for NATO operations. Because diesel engines can use JP-8, every single vehicle is fueled by it. Consequently, the fuel supply chain manages only a single type of fuel, which is a great advantage in military operations. But this implies that the performance of the Armed Forces depends on the crude oil market. Most European counties are oil-dependent; therefore, their Armed Forces depend on external agents.

1.2. CURRENT PROPOSED ALTERNATIVES

Several studies have addressed this issue. The most promising method is the development of alternative fuels [6]. But the development of a suitable alternative fuel has proven difficult. By now, most studies have been only partially successful [7, 8]. Besides, the fuels obtained are sometimes of very poor quality and problematic in engines [9]. Moreover, gas fuels, such as hydrogen or methane, are not suitable for military use. At first, they are stored under pressure. Thus, the piercing of the fuel tank means the total loss of the fuel within seconds, leaving the vehicle unpowered. Furthermore, they are highly inflammable [10] and can promote catastrophic explosions.

On the other hand, electric batteries are also not suitable for powering military vehicles; they cannot store a sufficient amount of energy [11] and are vulnerable to attacks. Finally, the recharge of batteries takes a long time and requires a powerful grid connection, which is not available on battlefields.

1.3. THE BIOMASS PELLETS AS ALTERNATIVE FUEL

Currently, biomass from agricultural and forestry byproducts is a poorly used energy source with great potential [12]. For example, the potential production of biomass in Spain [13] equals the amount of diesel fuel consumed [14], both measured in terms of power. However, the use of biomass as a fuel is currently restricted to heating applications. Biomass burns in the solid state and cannot be used in current internal combustion engines, which use liquid or gas fuels. There have been attempts to build solid fuel engines which could be fuelled by biomass, but they have been unsuccessful [15 - 17].

Therefore, the development of a functional Biomass-Fuelled Engine (hereinafter BFE) is very attractive. This way, as part of a doctoral dissertation, the thermodynamic cycle of those engines was studied and published [18]. Subsequently, a functional biomass-fuelled engine prototype was manufactured from the engine of a farm tractor (Figure 5). The start-up of the prototype engine demonstrates that biomass can be considered a viable alternative to fossil fuels in applications where internal combustion engines are required. An article explaining the principles for the design of a BFE, is expected to be published son.

Nevertheless, as an alternative fuel, biomass pellets have great advantages: (1) they are widely available in large quantities, so they can replace a large amount of petroleum-based fuels that are currently used; and (2) they can be safely stored in vehicles. However, they have the following disadvantages: (1) its energy density is lower than that of petroleum-based fuels [19]; (2) it cannot flow through a pipe as liquids do; thus, its management is more complex; and (3) it is very hygroscopic, making its use in water or humid environments difficult.

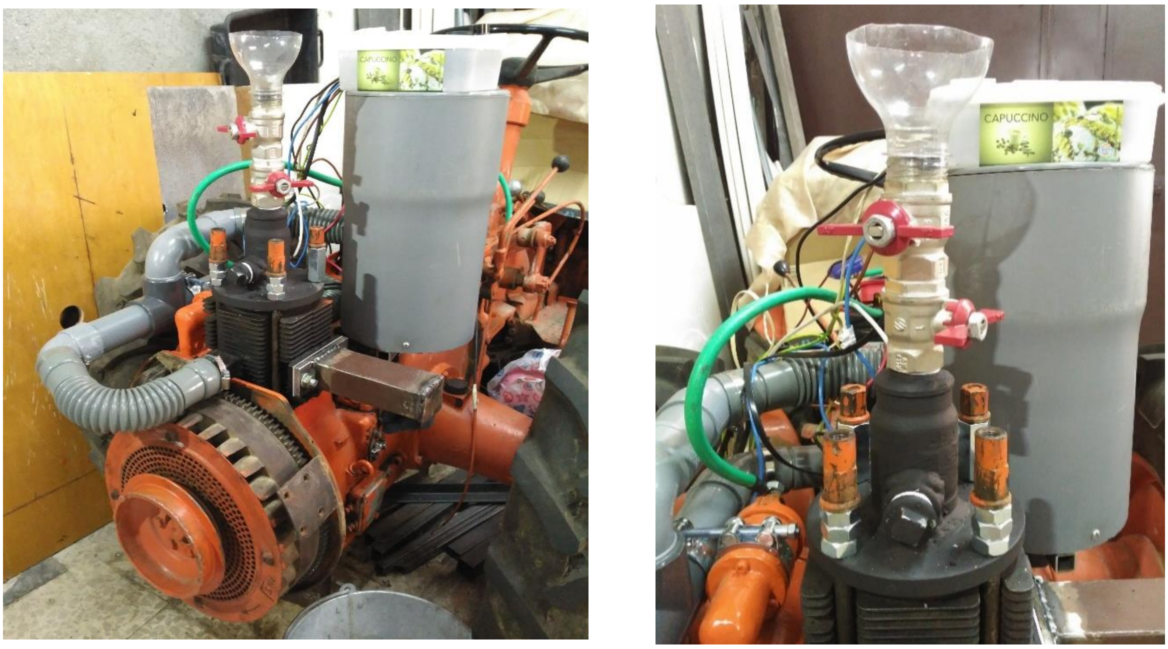
(a) (b)

Figure 5. (a) Biomass-fuelled prototype engine; (b) close-up of the combustion chamber and fuel feeder.

2. THE BIOMASS AS MILITARY FUEL

2.1. APPLICATION SCOPE

The BFEs are not suitable for all military applications. First, the lower energy density of biomass prevents its use in aircraft and other applications where fuel weight is an important limitation. Additionally, biomass pellets are highly hygroscopic. If submerged in water, they absorb large amounts of it, becoming useless. Therefore, the use of BFEs in boats and amphibian vehicles should be carefully studied. In contrast, land vehicles are less sensitive to weight, and the fuel can be easily kept dry inside the tank. Thus, the main military applications of BFEs will be land vehicles and power generators.

2.2. TECHNICAL FEASIBILITY

The BFEs must be developed before being used on military applications. A new engine development can take several years from initial concept to deployment. It involves extensive research and development, testing, and validation to ensure that new engines meet performance, efficiency, and regulatory standards. However, with adequate funding, BFEs are expected to be developed and deployed before 2035. Today, internal combustion engines are highly developed, and most research on diesel or gas engines can be applied to BFEs.

To take advantage of the present resources, the possibility of transforming current diesel engines into BFEs has arisen. Unfortunately, there are large differences between diesel engines and designed BFEs. Mainly, the combustion chamber of BFEs is much larger (the compression ratio is lower) and its shape is optimized for pellet burning. It lacks the turbulence required to burn liquid fuels. In addition, most of the current diesel engines are four-stroke engines. In contrast, the two-stroke design is more suitable for BFEs. Consequently, current engines cannot be transformed to be fuelled by biomass. For similar reasons, a 'hybrid' engine, capable of using both liquid fuel and biomass, is considered unrealizable. Instead, new developed BFEs are expected to fit on some of the current machinery.

2.3. IMPROVING CURRENT MILITARY CAPABILITIES WITH BIOMASS-FUELED ENGINES

The potential impact of the BFEs on the performance of Armed Forces can be summarized in four different fields (Figure 6).

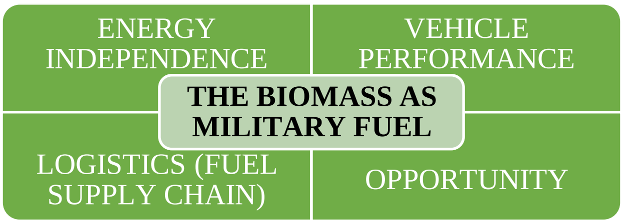

Figure 6. The impact of the BFEs on the performance of Armed Forces.

2.3.1. ENERGY INDEPENDENCE

Biomass is an energy source that is available in most European countries in significant quantities. The implementation of BFEs on military vehicles and power generators will make Armed Forces partially independent of external petroleum-based fuel supply. Therefore, in the case of a total shortage of petroleum-based fuel, the Armed Forces could still provide a response. Powered by biomass, most land vehicles would be fully operative. Personnel and weapon systems could be deployed and sustained. This is the most important advantage of the BFEs military application.

2.3.2. VEHICLE PERFORMANCE

It is true that a biomass fuel tank is heavier and more voluminous than a diesel fuel tank for the same stored energy. The additional weight will reduce the performance of the vehicle. However, military vehicles are usually equipped with armour. Currently, the fuel tank is one of the elements to be protected. If the fuel tank is pierced, the spillage and ignition of the fuel can defeat the vehicle and put the lives of the occupants at risk. Faced with this problem, self-sealing tanks [20] are used, which are an effective solution but also involves an increase in weight. That case, the use of biomass pellets as fuel has certain advantages:

1) In the case of fuel tank perforation, it is very difficult for the pellets to exit through the holes. The fuel is not lost, and the operability of the vehicle is maintained. If the holes are very large, the tank can be quickly repaired on-site using adhesive tape and similar materials. In addition, the spilled fuel can be recovered without harmful effects on the environment.

2) Biomass pellets are more difficult to ignite than liquid fuels and do not produce vapours that can form explosive mixtures with air. Furthermore, unlike liquid fuels, pellets do not soak surfaces. The spread of a fire is very difficult and its extinction is easier. Biomass fires can easily be extinguished using water. This makes biomass-fuelled vehicles safer and less prone to catch fire.

But there are more advantages. Biomass pellets are considered to be suitable material for absorbing energy and stopping secondary fragments. The pellet fuel tanks can be placed on the sides of the vehicle, acting as a spall liner in the case of total penetration of the armour. This would allow the fuel tank to be used as an active part of the armour, thereby saving weight. Additionally, the current empty space located just over the mine blast protection (in the lower part of the vehicle) could be used to store the pellets. In contrast to liquid fuels, a biomass pellet mass can be compressed because there is a lot of air in it. In the case of a blast, biomass pellets are compressed, absorbing the shock wave and preventing it from entering the cabin.

In conclusion, the use of biomass as fuel has beneficial effects on the performance of land vehicles. These advantages balance the increase in weight at least in part.

2.3.3. LOGISTICS (FUEL SUPPLY CHAIN) AND OPPORTUNITY

Today, the Single Fuel Concept prevents the use of fuels other than JP-8 or diesel fuel. The use of BFEs will require the creation of a different fuel supply line, making battlefield logistics more complex. But biomass sources can be found everywhere plants grow. As a result, on some battlefields a large amount of fuel could be obtained from the environment, releasing pressure from logistics. Only a woodchipper and pellet mill are required to take advantage of the available biomass resources. This implies a new tactical capability: the opportunity to obtain energy from the battlefield. It will allow some operations to be independent from fuel supply. This advantage was highlighted during the last Russian invasion of Ukraine. Lots of Russian vehicles were stopped because of the scarcity of fuel (Figure 7) being surrounded by biomass resources.

Figure 7. Aerial photo of a Russian convoy, out of fuel, in the middle of a Ukrainian forest in March 2022 (Maxar Technologies).

2.4. INTEROPERABILITY

Fuel can be an extremely valuable resource in a military operation. Since biomass can be obtained from the environment, the use of BFEs can save large amounts of liquid fuel during long-term military operations. Consequently, liquid fuel can be reserved for aircrafts or other valuable systems. That can be a decisive advantage in case the operation is not accomplished on time. The entire operation can fail if it lasts longer than planned and the vehicles run out of fuel (Figure 7).

2.5. BUSINESS CASE

Now, the BFE is in its early stage of development. Reliable, low-maintenance engines must be developed before using them on military applications. Fortunately, BFEs are expected to have civilian use. Consequently, their development costs can be shared and therefore reduced for the defence sector. Once suitable BFEs were available, trucks and power generators should be the first machines to be biomass-fuelled. They are not very sensitive to weight increment and biomass fuel tanks can be easily installed on them. Subsequently, deeper studies will be necessary to adapt BFEs to other platforms. However, the performance of the armed forces can be greatly improved even if only trucks and power generators are biomass-fuelled.

3. CIVILIAN APPLICATIONS OF THE BIOMASS-FUELED ENGINES

In addition to their military applications, BFEs are suitable for civilian use. Particularly, BFEs are very suitable to power agricultural machinery. If powered by BFEs, they will allow both food and fuel to be obtained from the same parcel (Figure 8) making food production independent of fossil fuels.

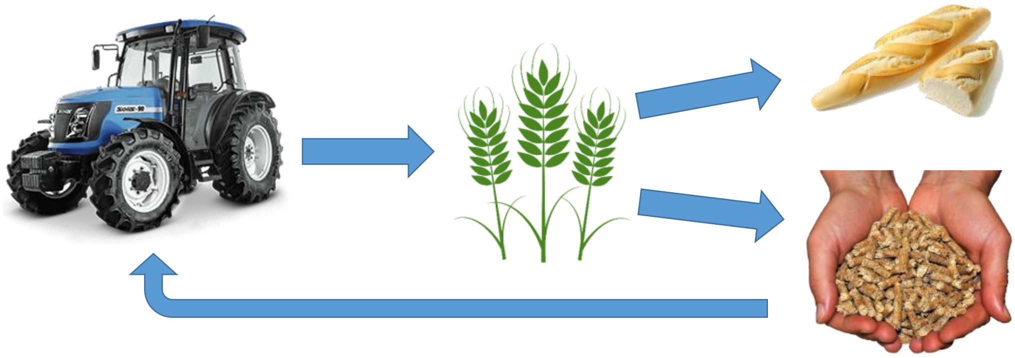

Figure 8. BFEs allow to obtain both food and fuel from crops.

Other large vehicles such as trucks or excavators may be powered by BFEs. In short, BFEs will be suitable to power a machine if the following conditions are met: 1) the engine is large enough to allow fuel pellets to move freely through the combustion chamber, 2) the machine is not sensitive to weight increment, and 3) a suitable fuel tank can be installed on it. Lots of machines that are used today accomplish these three conditions. Therefore, there is a large market for BFEs in civilian applications.

4. CONCLUSIONS

Biomass is a fully renewable and widely available energy source with great potential. Biomass-Fuelled Engines (BFEs) are a promising way to take advantage of it. Some important military systems can be powered by them. Today, military operations depend on petroleum-based fuel. The implementation of BFEs will allow them to be only partially dependent. In addition, as biomass can be obtained from the environment new tactical possibilities are open. Finally, biomass-fuelled vehicles will be safer when under attack.

Furthermore, BFEs will have many civilian applications such as agricultural machinery or trucks. Biomass is a carbon neutral fuel. The carbon dioxide emitted during combustion is reabsorbed during plant growth. Therefore, BFEs can support the decarbonization of important activities. Finally, the use of BFEs will have a positive impact on society. The increase in biomass demand will make a sustainable alternative to stubble burning, which represents pollution release and energy waste. In addition, forestry by-products will become a valuable fuel, allowing the forest to be cleaned from wooden residues, thus helping to prevent wildfires. From an economic point of view, the use of BFEs will reduce the fuel imports, improving the balance of trade. Furthermore, employment will be promoted in rural areas, fighting against their depopulation.

5. ACKNOWLEDGEMENTS

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References

[1] Crawford, Neta C, (2019) “Pentagon Fuel Use, Climate Change, and the Costs of War”, Watson Institute of Public Affairs and Law, Brown University.
[2] Vázquez, Javier Feal, (2008) “El mundo actual del petróleo”, Boletín de Información, no. 303, p. 57-72.
[3] Masson-Delmotte, Valerie; et al., (2022) “Global Warming of 1.5 C: IPCC special report on impacts of global warming of 1.5 C above pre-industrial levels in context of strengthening response to climate change, sustainable development, and efforts to eradicate poverty”, Cambridge University Press.
[4] Hirsch, Robert L (2005) “The inevitable peaking of world oil production”, Bulletin of the Atlantic Council of the United States, vol. 16, no. 3, p. 1-10.
[5] Senior NATO Logisticians' Conference Secretariat (1997) “Fuels, Oils, Lubricants and Petroleum Handling Equipment”, NATO Logistics Handbook, Chapter 15.
[6] Stančin, H.; Mikulčić, H.; Wang, X.; Duić, N (2020) “A review on alternative fuels in future energy system”, Renewable and sustainable energy reviews, vol. 128, p. 109927.
[7] Pimentel, David (2003) “Ethanol fuels: Energy balance, economics, and environmental impacts are negative”, Natural resources research, vol. 12, p. 127–134.
[8] Fore, Seth R.; Porter, Paul and Lazarus, William (2011) “Net energy balance of small-scale on-farm biodiesel production from canola and soybean”, Biomass Bioenergy, vol. 35, p. 2234–2244.
[9] Chiaramonti, David; et al., (2003) “Development of emulsions from biomass pyrolysis liquid and diesel and their use in engines—Part 2: Tests in diesel engines”, Biomass Bioenergy, vol. 25, p. 101–111.
[10] Airgas (2022) “Safety data sheet: hydrogen”, available in: https://www.airgas.com/msds/001026.pdf.
[11] Wen, Jianping; Zhao, Dan and Zhang, Chuanwei (2020) “An overview of electricity powered vehicles: Lithium-ion battery energy storage density and energy conversion efficiency”, Renewable Energy, vol. 162, p. 1629–1648.
[12] Camia, Andrea; et al. (2018) “Biomass production, supply, uses and flows in the European Union: First results from an integrated assessment”, JRC Publications Repository, vol. 1, p. 47–67.
[13] Cabrera, Miguel; et al. (2011) “Evaluación del potencial de energía de la biomasa. Estudio técnico PER 2011-2020”, IDAE.
[14] CORES (2022) “Informe Estadístico Anual 2022”, available in: https://www.cores.es/es/publicaciones.
[15] Piriou, Bruno; et al. (2013) “Potential direct use of solid biomass in internal combustion engines”, Progress in Energy and Combustion Science, vol. 39, p. 169–188.
[16] Schnürle, Adolf (1924) “Verbrennungskraftmaschine”, patent no. DE000000398997A.
[17] Firey, Joseph. C. (1983) “Char and oil burning engine”, patent no. US4412511.
[18] Suanes, Gonzalo; Bolonio, David; Cantero, Antonio (2023) “Definition of the Thermodynamic Cycle of a Biomass-Fueled Internal Combustion Engine”, Energies, vol. 16, issue 2, p. 896.
[19] IDAE (2020) “Lower heating values of the main wastes”, available in: https://www.idae.es/sites/default/files/estudios_informes_y_estadisticas/poderes-calorificos-inferiores_pci_v_1-00_2020.xlsx.
[20] Hutchinson Industries Inc. (2023) “Self-Sealing Fuel Tank Protection | Hutchinson Safetank”, available in: https://www.hutchinsoninc.com/protected-fuel-tank/.

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EUROPEAN HYPERSONIC SPACE DEFENDER

J. J. Navlet[1]

Abstract

Fifth-generation fighters like the F-35, the Sukhoi Su-57 and the Chengdu J-20 have given aerial supremacy to our allies and rivals while our fourth-generation Eurofighter is completing its life cycle. FCAS, the future EU air combat system, is expected to arrive in a very competitive market with an uncertain balance of power. As lagging behind is not an option and the European Union has the technology and capabilities to be ahead of the game, INTA researchers have begun developing long term upgrades. Relying on the new refracting materials of our partners, we are working on an ultralight 3D-printed fuselage with 9 through channels that can hold up to 13 different engines (turbojets, scramjets, rocket engines, plasma thrusters and D-Drive) to power a multi-drive single-stage-to-orbit space plane, capable of patrolling air and space if required and landing undamaged at an airport after reentry as many times as a reliable plane does.

Keywords

NGWS – NGF – FCAS – GCAP – Eurofighter, Space Defence, Single-Stage-to-Orbit Space Plane, Thermal Shield, Quantum Communications.

1. INTRODUCTION

Our Eurohunter Programme (2025-2050) has been conceived to pursue a fighter capable of reaching orbit and patrolling space relying on the power collected by the solar panels covering all the exposed surface of a Ø50m deployable and foldable antenna, as shown in figures 1 and 3c.

Figure 1. Blue prints and 3D views of the three configurations (airplane, space and reentry) of the 7th Generation Eurohunter Blizzard multirole fighter and space defender.

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[1] INTA (National Institute for Aerospace Technologies), Madrid, SPAIN

The **Eurohunter Blizzard** has been created as a further evolution of the FCAS – GCAP New Generation Fighter belonging to the NGWS. It inherits all its capabilities and provides an expanded architecture made of a flexible refracting fuselage that can stand hypersonic speeds all the way into orbit and take reentry overheating. It has room for different types of extra engines and incorporates the deliverables of INTA's ESSP project, which are a new plasma thruster (ARET) and a new quantum drive (D-Drive), both powered by the solar and space radiation collected by the antenna shown in figures 1 and 3c. It will also equip a new instantaneous infrastructure-less quantum communication system that will be delivered by INTA's QUANTEL project.

2. TIME LINE

Figure 2 charts the timeline of the **Eurohunter Programme** encompassing two research INTA projects, ESSP and QUANTEL. Both will develop the extra capabilities that we need to upgrade the New Generation Fighter (FCAS – GCAP) to make it a real Hypersonic Space Defender System (HSDS) that will serve as a deterrence to keep Europe safe from eventual foreign attempts to turn space into an operational domain during the rest of the 21st century.

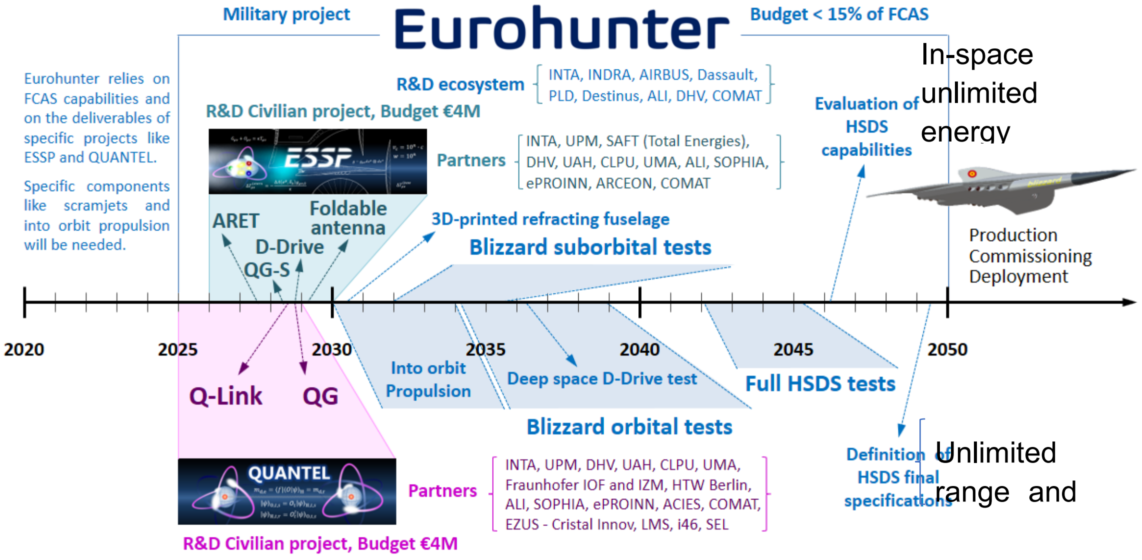

Figure 2. Timeline chart of Eurohunter Programme including ESSP and QUANTEL projects.

3. ONGOING INTA PROJECTS

3.1. EUROHUNTER

As shown in figure 2, Eurohunter is a long-range programme encompassing other civilian and military projects. It will evolve according to test results, to the final specifications of the NGF, to the composition of its consortium and to the role of deterrence in the future European Defence Strategy. Its enabler is ARCEON's new refracting fuselage material1 that acts a thermal shield.

3.2. EUROPEAN SOLAR SPACE PLANE (ESSP)

ESSP is a €4M civilian project that pursues a non-rocket launch into space relying mostly on solar power. It has 3 complementary research lines: big deployable solar panels, hypersonic spacecraft architecture, and space quantum propulsion based on vacuum (spacetime metric) engineering [1].

The first research line will develop and construct a scale prototype of a new 50 meter diameter deployable and foldable antenna covered with photovoltaic panels to increase up to 30 times the capacity of a regular satellite to collect solar energy in space, as it is shown in figure 3c. This antenna will be deployed above 100 km altitude, in the vacuum of space.

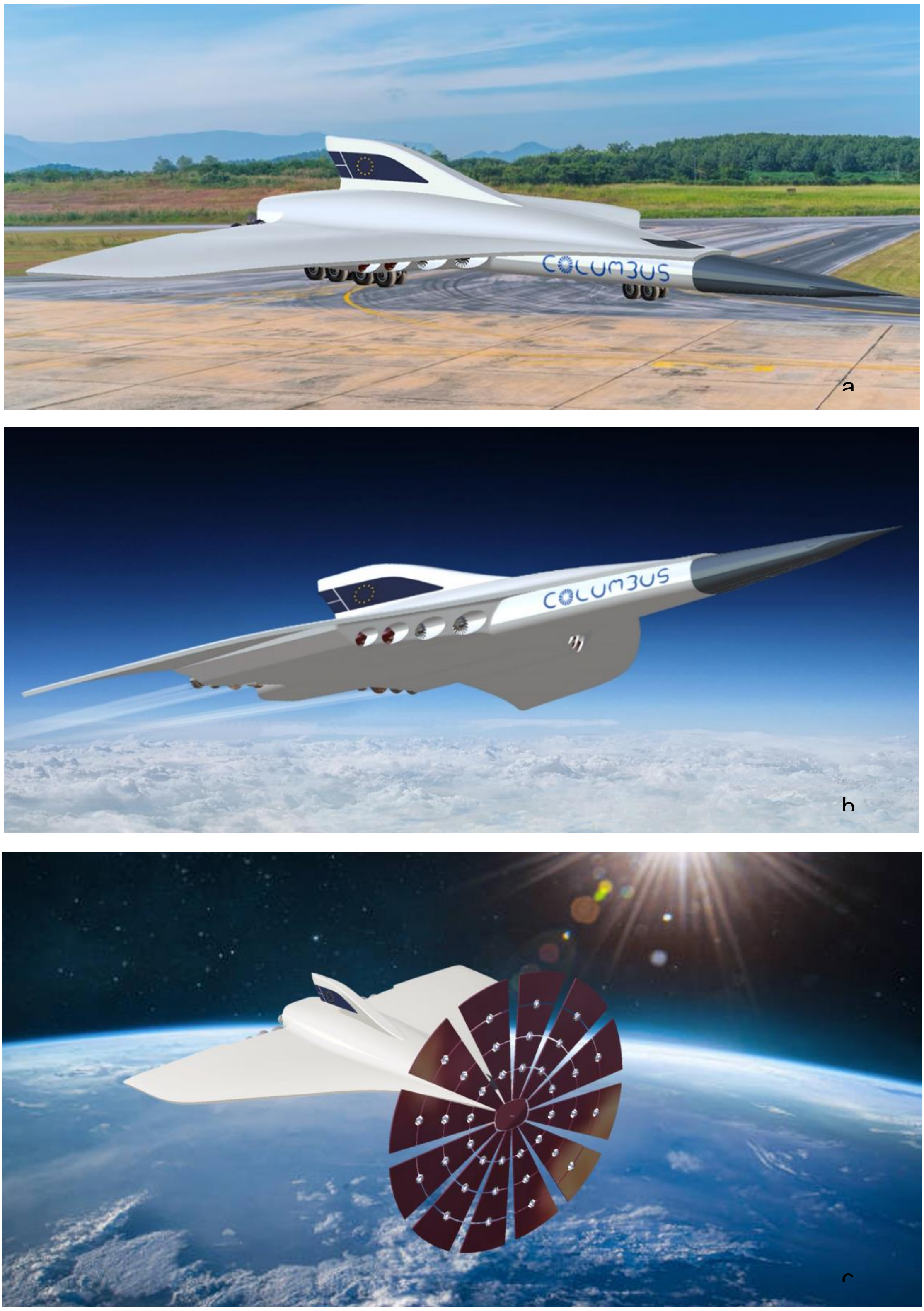

Figure 3. Columbus space plane (civilian version of the Blizzard) taking off in the airport (a), reaching 80 km with scramjets (b) and deploying its antenna in Low Earth Orbit (c).

The second research line will design the architecture of a light solar space plane, named Columbus (figure 3), made of a 3D printed polymeric fabric coated with ARCEON's refracting material1, which is lightweight, quasiductile and can withstand twice the temperature that melts steel. This material has been successfully used to produce rocket nozzles and spacecraft re-entry heat shields.

In the third research line we will develop and construct a demonstrator of a new type of asynchronous plasma thruster (ARET) and a convenient quantum material to build an active shield, named Quantum Gravity Shield (QG-S), that converts radiation into spacetime metric fluctuations. The combination of QG-S and ARET, called D-Drive (figure 4), can theoretically use those fluctuations to power a quantum drive for orbital manoeuvres and in-space propulsion.

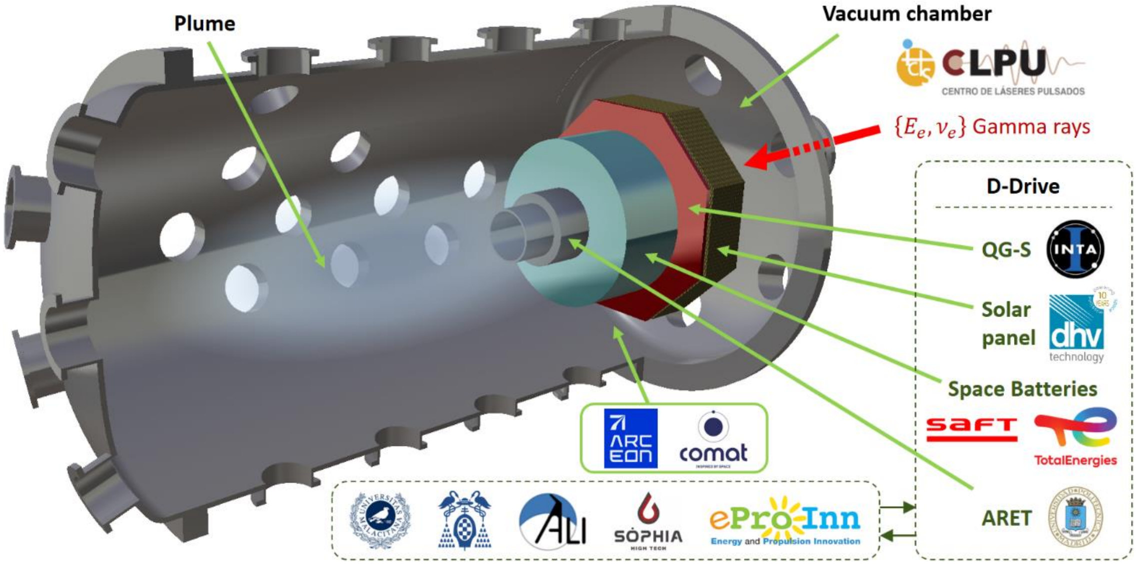

Figure 4. Small-scale D-Drive demonstrator absorbing electromagnetic radiation close to the Bose-Einstein-Condensate temperature during a test inside an Oerlikon vacuum chamber.

The model that delivers the equations of our D-Drive replaces the cosmological constant Λ in the Einstein Field Equations for a function $\Lambda(e^{\mu}, \delta)$ that encompasses the effects of dark matter and dark energy in the curvature of the Riemannian manifold that Einstein used to formulate his General Theory of Relativity (GTR). Splitting $\Lambda(e^{\mu}, \delta)$ into its terms and grouping them into the **Einstein tensor** $G_{\mu\nu,\delta}$ plus our **Order tensor** $O_{\mu\nu,\delta}$, we substitute Λ by the term $O_{\mu\nu,\delta}$, which introduces in the domain (e^{μ}, δ) the effect of an unmeasurable local redistribution of dark matter and dark energy produced below 4 K by radiation. This yields the **Dark Field Equations**:

- $\Lambda(e^{\mu}, \delta) = \frac{12G}{\delta^3 \cdot c^2}\left[f_d \cdot m_b(e^{\mu}, \delta) - E_d^{\infty}\frac{\delta^3}{{r_m}^3} + \Delta m_d(e^{\mu}, \delta) - \frac{\Delta E_d(e^{\mu}, \delta)}{c^2}\right] = \kappa T_{\mu\nu}$
-
- $O_{\mu\nu} = \frac{12G}{\delta^3 \cdot c^2}\left[-E_d^{\infty}\frac{\delta^3}{{r_m}^3} + \Delta m_d(e^{\mu}, \delta) - \frac{\Delta E_d(e^{\mu}, \delta)}{c^2}\right] g_{\mu\nu}$
-
- $G_{\mu\nu} = R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} = \frac{12G}{\delta^3 \cdot c^2} f_d \cdot m_b(e^{\mu}, \delta) g_{\mu\nu}$

- $G_{\mu\nu} + O_{\mu\nu} = \kappa T_{\mu\nu}$

Dark Field Equations

The expansion of the universe caused by dark energy is the component $-E_d^{\infty}\frac{12G \cdot \delta^3}{\delta^3 \cdot c^2 \cdot {r_m}^3} g_{\mu\nu}$ of term $O_{\mu\nu}$, and the equation of the D-Drive is

- $\Delta T_{\mu\nu,\delta} = \frac{12G}{\delta^3 \cdot c^2}\left[\Delta m_d(e^{\mu}, \delta) - \frac{\Delta E_d(e^{\mu}, \delta)}{c^2}\right] g_{\mu\nu}$

Our cosmological model is adjusted to stop the expansion of $\mathbb{G}_U$ (visible universe) when the kinetic energy of the relativistic mass equivalent of dark energy equals the relativistic energy or dark matter. The limit velocity v is

$$\frac{1}{2}\frac{|E_d|}{c^2}v^2 = m_d \cdot c^2 = |E_d| \quad \Longrightarrow \quad \frac{v^2}{2c^2} = 1 \quad \Longrightarrow \quad v = \sqrt{2}c = 423970560\ [\mathrm{m} \cdot s^{-1}]$$

Figure 5 shows the topological model to alter the balance of dark mass and dark energy that we need to operate the hyper D-Drive with incident solar or cosmic radiation. The inflation of dark energy in the domain (e^{μ}, δ) of the spaceship is equivalent to the production of the negative energy required to operate the **Warp Drive** in the article “The warp drive: hyper-fast travel within general relativity”, Prof. Dr. Miguel Alcubierre, University of Cardiff, 1994 [2].

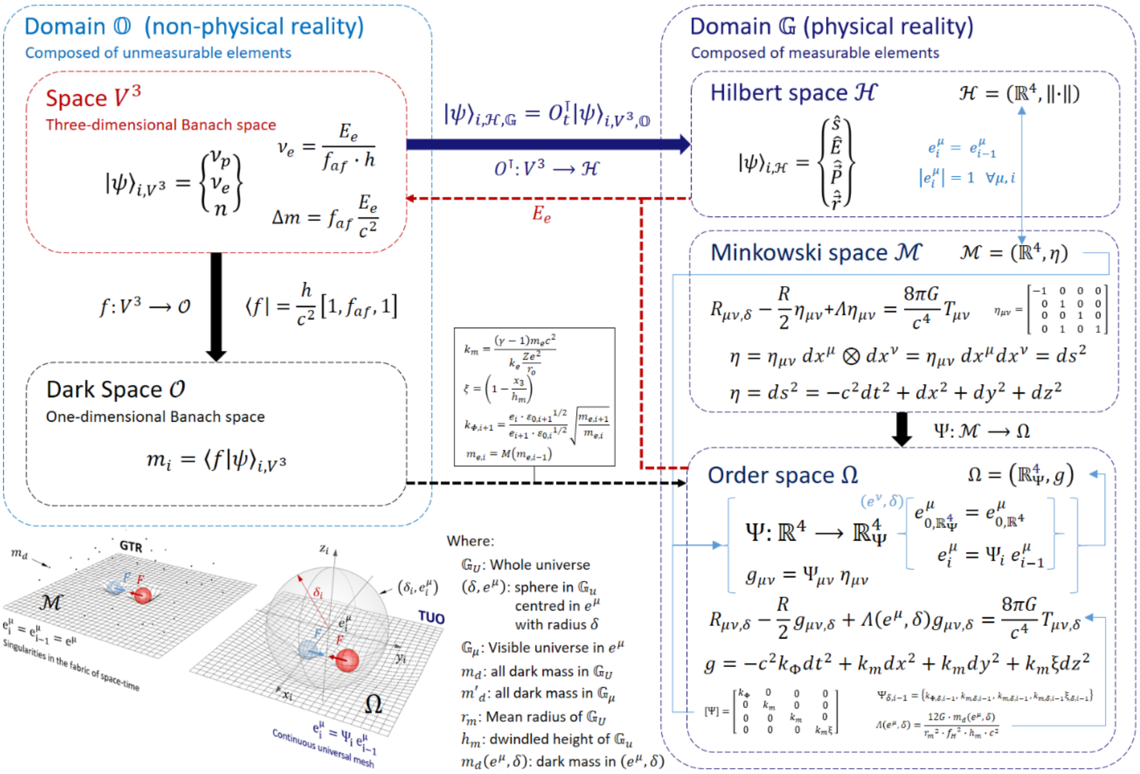

Figure 5. Algebraic and topological model to obtain the equations of the D-Drive from GTR.

In summary, the ultimate goal of ESSP is to replace current chemical propellants with a new innovative low cost and eco-friendly solar propulsion solution, and to turn most harmful space radiation into a power source to increase spacecraft speed and limit radiation dose to space crews to a safe level, making manned deep space missions feasible.

3.3. QUANTUM NOISE TELEPORTATION (QUANTEL)

QUANTEL is a project with a €4M budget that pursues a Quantum Entanglement Communication Link (Q-Link) capable of establishing an instantaneous communication between two remote points in space without physical connection based on the entanglement [3] of the oscillation of the state of two remote hadrons, which occurs when they are tuned into the same quantum band.

To achieve this goal (interoperable dual quantum communication system with the aforementioned specifications), we have resorted to a new THEORETICAL FRAME FOR QUANTUM ENTANGLEMENT. Being

$$|E\rangle_{\mathcal{H}} = |A\rangle_{\mathcal{H}} \otimes |B\rangle_{\mathcal{H}}$$

the expression of the **quantum entanglement** $|E\rangle_{\mathcal{H}}$ of the quantum states $|A\rangle_{\mathcal{H}}$ and $|B\rangle_{\mathcal{H}}$ of two particles A and B in the Hilbert space $\mathcal{H}$ belonging to $\mathbb{G}$, we define the entanglement equivalence

$$|E\rangle_{\mathcal{H}} = |A\rangle_{\mathcal{H}} \otimes |B\rangle_{\mathcal{H}} \;\equiv\; \left\{ g_{\mu\nu}\, dx^{\mu} \otimes dx^{\nu} = 0 \;\cup\; \left| \frac{\sigma_{|A\rangle_{V^3,\mathcal{O}}|B\rangle_{V^3,\mathcal{O}}}}{\sigma_{|A\rangle_{V^3,\mathcal{O}}} \cdot \sigma_{|B\rangle_{V^3,\mathcal{O}}}} \right| \simeq 1 \right\}$$

which establishes that, according to the superposition principle applied to multi-particle systems, the quantum entanglement of quantum states $|A\rangle_{\mathcal{H}}$ and $|B\rangle_{\mathcal{H}}$ of the two particles A and B **is equivalent to a metric entanglement** $g = g_{\mu\nu}\, dx^{\mu} \otimes dx^{\nu} = 0$ of the quantum states $|A\rangle_{V^3,\mathcal{O}}$ and $|B\rangle_{V^3,\mathcal{O}}$ of the same particles A and B in the convenient set of spaces $\{V^3, \mathcal{O}\}$ belonging to the algebraic subset $\mathbb{O}$ such as $V^3 \in \mathbb{O}$ and $\mathcal{O} \in \mathbb{O}$, **plus a simple statistical correlation** of their states $|A\rangle_{V^3,\mathcal{O}}$ and $|B\rangle_{V^3,\mathcal{O}}$. $\mathbb{O}$ is the subdomain of reality encompassing unmeasurable entities.

Then, if V^3 and $\mathcal{O}$ are related by linear function $f: V^3 \longrightarrow \mathcal{O}$, also denoted $\langle f|$ in Dirac notation, and we consider a quantum state $\langle H_m \rangle$ in $\mathcal{O}$, the expression is simplified such as

$$|E\rangle_{\mathcal{H}} = |A\rangle_{\mathcal{H}} \otimes |B\rangle_{\mathcal{H}} \;\equiv\; \langle H_m \rangle_A = \langle H_m \rangle_B$$

because it holds the metric entanglement in $\mathcal{O}$ as $g_{\mathcal{O}} = ds^2_{AB} = 0 \Longrightarrow x_A = x_B$, and $\langle H_m \rangle_A$ and $\langle H_m \rangle_B$ are correlated as we have imposed the condition $\langle H_m \rangle_A = \langle H_m \rangle_B$, which yields $r = 1,\ \forall x = y$.

Let $\langle H_m \rangle$ be the quark condensate term $\langle H_m \rangle$ of the QCD mass decomposition M of a proton [4], which implies that $x_i = \nu_i = c^2 \cdot \langle H_m \rangle_i / h$. If we assume that $\langle H_m \rangle$ belongs to $\mathcal{O}$, being

$$M = 0{,}09\langle H_m \rangle + 0{,}32\langle H_E \rangle + 0{,}36\langle H_g \rangle + 0{,}23\frac{\langle H_a \rangle}{4},$$

where $\langle H_m \rangle$ is the quark condensate, $\langle H_E \rangle$ is the quark energy, $\langle H_g \rangle$ is the gluon field energy and $\langle H_a \rangle / 4$ is a trace anomaly, the quark condensate term $\boldsymbol{\langle H_m \rangle_A}$ of the QDC mass decomposition of same-energy-level protons **located in lattice A will be metrically entangled to** the quark condensate term $\boldsymbol{\langle H_m \rangle_B}$ of the QDC mass decomposition of same-energy-level protons located in remote lattice B if $\langle H_m \rangle_A = \langle H_m \rangle_B$. Then, as the existence of the Higgs field [5] implies that there is a quantum spectrum, if $\mathcal{O}_A = \mathcal{O}_B$, where $\mathcal{O}_A, \mathcal{O}_B \in \mathbb{O}$, a metric entanglement in $\mathbb{O}$ requires no previous physical connection and guaranties quantum coherence regardless of distance.

Consequently, if we add the condition that $\boldsymbol{\langle H_m \rangle}$ **is quantized in narrow bands of a continuous quantum spectrum in** $\boldsymbol{\mathcal{O}}$, the random oscillation of $\langle H_m \rangle$, also named quantum noise and denoted $\Delta\langle H_m \rangle$, would be instantaneously shared between all metrically entangled protons in lattice A and lattice B, no matter how remote A and B might be, because the simplified expression guarantees that there is quantum entanglement between A and B. Figure 6 shows how those quantum states are related to macroscopic parameters of electromagnetic excitations supplied to lattices A and B.

$$\langle H_m \rangle = \langle f|\psi\rangle_{\mathbb{O}} \in b = \{\langle f|\psi\rangle_{\mathbb{O},0} - \Delta m, \langle f|\psi\rangle_{\mathbb{O},0} + \Delta m\}$$

$$\langle H_m \rangle = \langle f|\psi\rangle_{\mathbb{O}} = \langle f|\psi\rangle_{\mathbb{O},0} + \langle f|\psi\rangle_{\mathbb{O},\mathrm{r}} = \frac{h}{c^2}\nu_0 \cdot z_s + \frac{h}{c^2}\nu_n + \frac{E_H}{c^2}$$

$$\Delta m = \Delta\langle f|\psi\rangle_{\mathbb{O}} = \langle f|\psi\rangle_{\mathbb{O},\mathrm{r}} \simeq \frac{E_H}{c^2} = \frac{h \cdot \Delta\nu}{c^2} = \frac{f_n \cdot f_{af} \cdot f_a \cdot V_S \cdot I_S}{f \cdot c^2 \cdot n_p}$$

$$\left.\begin{array}{l} I_R = \int_S \vec{J} \cdot d\vec{S} \\ \vec{J} = \frac{1}{\Delta v} \sum_{q_i \in \Delta v} q_i \cdot \vec{v}_i \end{array}\right] \begin{array}{l} I_R = \frac{n_p \cdot q_p \cdot o \cdot \bar{a} \cdot f_f}{l} \\ V_R = \frac{f_f \cdot E_R}{I_R} = \frac{f_f \cdot E_H \cdot n_p}{f_{af} \cdot I_R} = \frac{f_f \cdot h \cdot \Delta\nu \cdot n_p}{f_{af} \cdot I_R} \\ f_f = f \end{array}$$

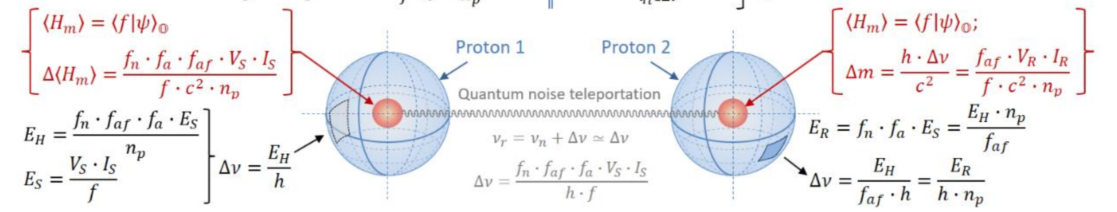

Figure 6. Teleportation model based on the introduction of a quantum noise signature in a quantum spectrum energy band b in $\mathcal{O}$.

The physical principle of the teleportation is the conversion of an electromagnetic signal containing information into a quantum noise signature under the zero-point energy that occurs in the lattice A of a sender Q-Link (figure 7). This quantum noise signature can be instantaneously shared without energy exchange by a remote lattice B in a receiver Q-Link when its massively entangled protons are tuned into the same Quantum Energy Band, because it replaces the natural random pattern of its quantum noise with the information-containing signature created in A.

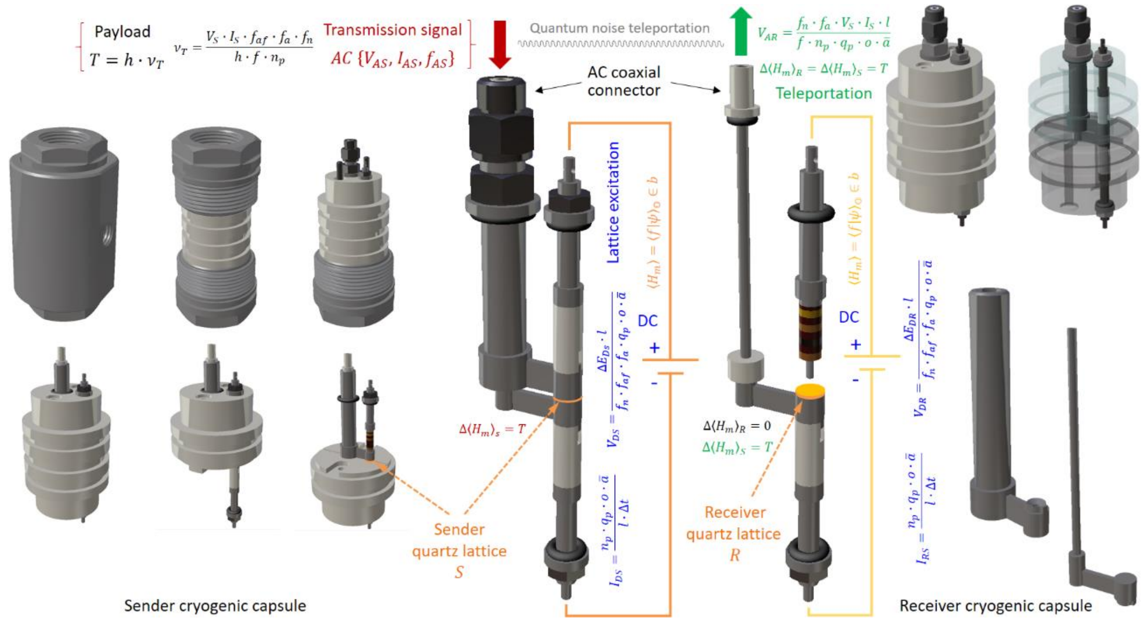

Figure 7. Cryogenic capsule containing the quartz lattice.

As $\Delta\langle H_m \rangle$ is below the zero-point energy of vacuum, it skips in this model the compulsory energy balance of the law of conservation of energy in the physical domain $\mathbb{G}$, where the Hilbert space $\mathcal{H}$ of quantum physics belongs.

However, skipping the energy balance comes with a toll. $\Delta\langle H_m \rangle$ is undetectable for our instruments unless we have a sufficient population of entangled protons in lattice B at a temperature low enough to dim thermal noise below quantum noise, where $\Delta\langle H_m \rangle$ will be naturally amplified to a level where an electronic amplifier would make it measurable.

Our calculations show that a macroscopic entanglement of 1021 entangled protons (e.g. in a lattice Ø 4 mm, 250 µm thick) at 4 K temperature naturally amplifies the quantum noise signature in B by 210 dB producing an AC (alternate current) signal that can be detected with a 50 dB amplifier.

In the end, what we are measuring in B is the same DC (direct current) energy that we are physically supplying to B, but our instruments will detect it as tainted with the amplified signature of the quantum noise that we are physically introducing in the sender lattice A by supplying the AC (excitation producing the transmitting signal T) to A.

4. CONCLUSIONS

In a world where deterrence is key to national security, Eurohunter will provide within a contained total investment (less than 15% of NGF budget) the dual technology that will eventually upgrade the FCAS – GCAP to guarantee that our rivals will not turn space into an operational domain.

Some components of this technology will be developed in ESSP project, which pursues bringing future civilian space planes to orbit as an alternative to current more expensive and polluting rockets, where they will be entirely propelled and powered by solar energy and space radiation.

In the space exploration arena, the replacement of current chemical propellants for a propulsion technology that consumes the harmful radiation in space will limit radiation doses to space crews to a safe level, making manned missions to Mars and beyond feasible.

As it pertains to QUANTEL project, the node of an instantaneous communication system based on the use of the quantum spectrum will be developed. The Q-Link, which is the name of this device, will provide an unbreakable information exchange without infrastructure and with a negligible energy consumption. The military application of this technology will guarantee the secure flow of information in the Defence Loop beyond the performance of current cybersecurity and current quantum technologies, both based on single photon emission or spin entanglement.

The Q-Link will also replace the 1.2 billion dollar NASA Deep Space Network for 50,000 € portable devices with better specifications such as wider broadband, no signal decoherence and no transmission delays like the 20 minutes that takes light to travel from Earth to Mars.

A miniaturization of the Q-Link will enable a new Quantum Generation cell phone technology (QG) that will operate without network infrastructure using the same quantum spectrum.

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References

[1] Harold E. Puthoff, “Advanced space propulsion based on vacuum (spacetime metric) engineering”, Institute for Advanced Studies at Austin, JBIS, Vol. 63, pp.82-89, 2010.

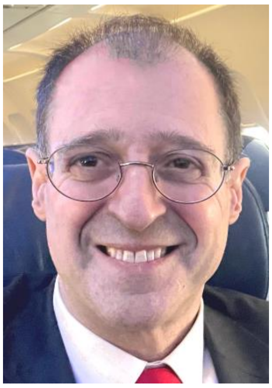
[2] Miguel Alcubierre, “The warp drive: hyper-fast travel within general relativity”, Department of Physics and Astronomy, University of Wales, College of Cardiff, 11-5, L73-L77 (1994).

[3] Zhen-Sheng Yuan, et al., “Entangled photons and quantum communication”, Physics Reports, Volume 497, Issue 1, December 2010, Pages 1-40.

[4] Yi-Bo Yang, et al., “Proton Mass Decomposition from the QCD Energy Momentum Tensor”, MSUHEP-18-017, PACS numbers: 11.15.Ha, 12.38.Gc, 12.39.Mk.

[5] CERN-PH-EP-2012-218, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”.

Author



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TELEDETECTION OF LAND OBJECTS SYSTEM (TELLOS)

A. L. Jiménez[1]

Abstract

The increasing presence of new ways to be exposed to military threats hinder a straightforward operative threat detection. At this point, a fast recognition cross-platform 360° aims to uncover the potential threat by tracking the conflict area through ground-based remote sensing of menaces is very necessary. This motivates the scientific community to find out for a safer, faster and more accurate solution which leads to a more compact technology to detect threats targeted to land force protection. In order to contribute to the further construction of a more efficiently standoff threat sensing-device than existing as far, our novel proposal is a Teledetection of Land Objects System (TelLOS) set-up by a multi-frequency spectroscopic and laser-based methodology for ranged detection of weaponry-targets. This System provides a multidimensional view to widen the assessment, effectiveness and enhancement of a neutralizing strategic decision from a faster threat identification with a more compelling response than currently.

Keywords

"Weaponry-target threats"; "Ranged ground-based multi-sensor technology"; "cross-platform 360° recognition"; "remote MM-w/THz/Raman-LiDAR/LIBS/hyperspectral"; "Land forces in conflict areas".

1. INTRODUCTION

Military threats are still nowadays emerging to settle unavoidable economic and diplomatic affairs, but the point is that those are increasingly being presented in new ways all over the world. The search for an efficient remote sensing technology over a platform to screen for all types of threat-objects —such as mines, IEDs or any other weapons both as hidden in the ground, by hostile assets clothes, by vegetation, and by tactical or civilian vehicles, and as non-hidden menace—susceptible to be operate over different types of platforms in real-time operation mode, is an ongoing research area that awaken interest with the main objective of promoting the defence of the land forces against the foe and aimed to diminish the conflict worldwide. Whilst sensors on-board a platform scanning system 360° around as threat-target seekers in the combat field to assess whether or not an incoming asset is one hostile has made barely inroads except for heaviest-like (e.g., tanks, artillery guidance).

Besides the commonly available systems to search explosives threats (i.e., mines and IEDs), a multi-sensor system that address the largest number of threat types is very necessary to be deployed in the combat fields to increase the responsiveness against an enemy attack. Greater information from a sample-target is obtained through a combination of complementary technologies, which enables to take action in a more accurately way by avoiding false positives detection occurrences.

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2. STATE-OF-THE-ART (SOA)

An inventory for weaponry-threat detection technologies, as well as the SoA knowledge in this matter it is necessary in order to address a research study of the technologies in the sight of the current threats, including its innovative development. But foremost, the materials hiding either explosives-containing objects or weapons play a decisive role in the detection of threats, due to the importance of the implemented system to make the detection. As starting point, a sensor may operate at the non-stop surveillance detection mode for the search of potential threats, and warn about a supposed identification of the suspicious target as a consequence.

This document highlights the importance of adequate instrumentation for direct or distant detection of suspected threats in the field subjected to an operational setting of the conflict zone.

2.1. IMPLICATIONS AND BENEFITS

Something meaningful to consider in the sensors for detection of combat threats is the possibility to operate as a mobile unit. In that sense, the implications by the use of the more suitable technology in this field contribute to a set of defence benefits impacting the subsequent tactical action of the land forces. It is a cutting-edge and suitable effort to increase early detection capacity of an attack from the opposing forces levering the foresight of further potential technology for threat detection in the land remote sensing field with the purpose of enhance the protection of the operative land forces.

2.2. PROBLEM STATEMENT

The framework context that demand the present document in which it will develop the field of work that concerns this proposal is the increasing conflict worldwide and war zones where it is necessary to monitor the potential menaces. These threaten the lives of all involved vital assets by using a non-standard technology with all the benefits of those considered to have the most highlighted features in a single instrument, in a rapid and remote way.

The types of target-threats may be either concealed, hampered, or hidden by potential barriers such as fabrics materials, objects (including vehicles), vegetation, soils, short-flight dangerous objects, or even as uncovered target. It is worth noting, however, that the constituents in the detection of ammunitions that use the weapons are mostly explosive or deflagrant compounds such as RDX, HMX, PENT, TNT, and a survey of the more frequent spectral signatures based on a complete detection of the greatest possible number of threats containing such substances is necessary to address the issue properly. Moreover, the problem to discern a target from a non-target threat rely on the technology endowed with the more suitable instrumentation enabled to accomplish the most correctness results, based on a methodology that covers all types of weaponry-menaces in order to recognize its shape and behaviour.

2.3. CURRENTLY EXISTING SOLUTIONS AND RECENT RESEARCH PROPOSALS

The ongoing research is aimed at overcoming the resolution of the topic presented in this proposal, whose novel contribution lays on the analysis of both current and emerging threats that can increase the existing database with the most suitable technology fitted for working as synergic mode, able to continuously scan a conflict area from a cross-platform spanning a 360° around in order to recognize the presence of potentials threats rapidly.

Currently existing solutions of this topic are fragmented over a wide variety of scientific publications. As far as we know, the best potential technologies in this concern issue on which the recent research proposals are hold up are laser-based spectrometric methods (through spectroscopic identification) like LiDAR and Raman techniques, being imaging methods in the GHz to THz domain (such as millimetre-wave imaging or THz imaging and spectroscopy) as complementary techniques to the laser-based detection methods providing information (e.g., warnings) about the presence of suspicious or concealed weapon-objects. Wallin et al. [1] support this proposal insight by referring at the laser and imaging-based as good complementary methods since potential technology for standoff detection and identification of explosives is targeted by the presence of threat-target devices, e.g., IEDs, or suspicious/concealed objects under clothing.

2.4. NOVELTY OF THE PROPOSAL

It is known that solely one technology is unlikely that encompass all pathways to threat detection since it is necessary to reach a balance of factors—such as selectivity, sensitivity, detection limits, spectral or imaging resolution, time-response capability or signal strength, signal-to-noise ratio (SNR) — that favours an effective detection of the widest possible range of target-threats, i.e. focusing on the strengths of each technology. Thereby, the combination of complementary techniques usually improves the selectivity of individual sensors. Indeed, the better the selectivity of the detection method, the less susceptible to other non-target constituents (or interferents). In addition, the combination of imaging and spectroscopy techniques can provide a more reliable match of potential targets in order to subsequent support a more confidence decision making. In fact, threat detection methods should be evaluated under rigorous testing for a given setup, and to have the possibility of choosing the wavelength range and the operational procedure will optimize the outcomes. All this together with the fact that under relevant conditions, like that generated in the battlefield, standoff detection methods of weaponry-threats need to be improved to achieve detection limits increasingly lower. Fusion of standoff sensors aids to address the object clutter allocation and improves the false alarm response.

In that sense, we explored the possibility of fusing the thorough generated "MM-w/THz/Raman-LiDAR/LIBS/hyperspectral" data with robust existing technologies for a reliable detection in order to pursuit the highest correctness of the results. THz spectroscopy and mm-wave technologies may be used as a complement to the laser-based methods, like Raman-LIBS, Raman-LIDAR, and Raman-hyperspectral. This synergic instrumentation is fitted with mature technologies already at a research stage and has components susceptible to be even more miniaturized, deployable, and portable. Indeed, this range of technologies can be tuned for detecting and identifying the different concealed explosives-containing threats by a number of possible materials and the presence of other weaponry target-threats.

A throughout survey of theoretical principles may guide the optimization of sensor parameters (i.e. factors above) in order to enhance the performance and configuration of the land system target detection. Once active sensors are operating, configurations of instruments to optimize the capture of light signal reflected from the threat-target into the detector to monitor the signals for optimizing the performance of the measurements are substantial to improve the precision in the identification of the menace objects. So that, when standoff method is applied, the functioning of all these devices is targeted to project focused wavelengths at a distance depending on the elements-containing the potential threat of the submitted scenario. Between these elements, we can have both moving and on-the-site targets, like platforms, including manned and unmanned vehicles, living beings, buried objects, close-flight objects. The faster the recognition and allocation of the threat, the faster the remote operator will take a later neutralizing action.

When a spectroscopic technique is tuned to characterize a possible hazardous composition of a supposed threat-target, needs to cope different limitations, such as spectral signatures from the molecules of interest, like that of explosive or deflagrant substances. For example, the revealed spectral features from explosives have inherent difficulty to be obtained because of their larger molecular size in comparison with those of smaller size of the typical atmospheric monitoring.

The sensors for detection of concealed, hidden, uncovered or in-flight threats lead to different technical solutions to be addressed from distinct action framework. Within this context, we scope four stages: (1) THREAT ASSESSMENT: a preliminary analysis based on the knowledge of the available threats mentioned above within our reach; (2) SETTING THE MULTI-SENSOR FOR DETECTING THREATS: to undertake a tightness inventory of the more reliable sensors for detection of all those threats and a thoroughly diagnostic thereof by feature extraction and classification of threats considering the proposed scenario; (3) IMPLEMENTATION OF THE MULTI-SENSOR ONBOARD A CROSS-PLATFORM 360°: to prove the feasibility of this technology over a cross-platform 360° for this threat recognition purpose; (4) PERFORMANCE OF THE MULTI-SENSOR: the functioning of this technology which proved to be the most trustworthy in a scenario as close to reality as possible.

As a starting point, this proposal would be aimed at simulating the detection of a wide spectrum of weaponry objects (WOs) and weaponry related objects (WROs) through knowing realistic threat that a sensor would scan from possible truth scenarios. In this line of sight, we engage in the novel proposal described along this document which is based on the remote sensing of weaponry-threat targets with prospects to be mounted on a cross-platform 360° and that gather the most effective technologies in the standoff threat detection field enabling to span an exhaustive diagnostic (detection, recognition, identification, discrimination, analysis, localization, verification, characterization, tracking) of the land force scenario where the threats are present from an imaging and spectroscopic prospecting framework. With this proposal of a continuous prospection of an hypothetical and unfortunately frequent conflict scenario involving the land forces, searching for ranged threat-targets, we refer to TelLOS, and it is aimed contribute to the defence of the armed force in an appropriate way in a setting where the faster and more accuracy action of sensing threats at standoff and direct distances can save lives. Once there is a technology integrating all these proposed techniques, deploy a set of prototype devices distributed across the multi-platforms and working as a network system could generate a deepest insight rendering additional information with a more tight overarching response as promptly.

3. METHODS AND SCIENTIFIC APPROACH

Detection and discrimination of a target-object from the innocuous one according to a library or database obtained from an exhaustive analysis about all the possible diagnosed threats and their precursors, is constrained to the detection method used for this purpose. For this reason, a comprehensive set of targets needs to be measured in order to build an effective database of weapon threats and their most significant constituents. In this regard, we can resort to a method based on get both imaging and spectroscopic features which aids to discern between a target and a non-target threat with a high probability that the object matched as a threat in order to take a rapid decision by reducing the false positive/negative outcomes. To achieve this, we use complementary techniques meaningful in this field which offer an imaging and spectroscopic prospect through several imaging-based and laser-based spectrometric technologies, because the drawbacks in one technique is offset with the potentialities of the other one. Besides, while the imaging-based technology may provide information about the presence of a key target, the laser-based technology could be functioning as a sensor that identify and verify the suspicious threat.

Note that the mentioned complementary methods, based on laser and imaging target tracking, can be found in the same technology or in separate ones. Nevertheless, this proposal is aimed to the further performance of a relevant remote sensing technology integrating all the potential scanning methods selected as the most promising that might detect ranged a potential threat close to the involved assets in defence within the conflict scenario as promptly. Furthermore, the materials hiding the explosive devices or the weapons play a decisive role in the detection of threats, due to the importance of the implemented system to make the detection.

3.1. ANALYSIS OF OPTIMUM DETECTION TECHNOLOGIES

The differences in the intensity of the received radiation compared to that without the target may indicate the presence of threat-object, from the complementary imaging or spectroscopic feature response. For fielding the most effective technologies from between all considered in this document (see below), it is necessary to face the technical parameters of each instrumentation. Specifically, the most desirable criteria for setting the multi-sensor for detecting threats are mostly the following: high selectivity and sensitivity, low false positive/negative response, a wide range of detectable target-threats, high spectral and spatial resolution, low LODs, high range-resolved measurements. Also, the velocity of the detection technique is a relevant factor to consider since a higher velocity may avoid a personal damage upon a potential detonation of a weapon-threat. Resolution is a significant factor for all these techniques due to it indicates how accurately identify and classify target-objects. On the other side, the selectivity is a measure of the impact of interfering objects on the quality of threat-target detection, and the sensibility is known as the probability of detection of the target-object. The atmospheric transmission is another important factor to consider because of the wave-length concerned to the detection technology, owing to the settings make up from the theatre of operations might affect the returned light from the deployed active sensor. The limit-of-detection (LOD) of the technique for sensing threat objects including the explosives-containing, even the residues of those hazardous substances at a level trace, mostly depends on: the distance from the target material, the type of threat, the laser properties, the substrate material in which the target is present, the matrix effects that affects the , the presence of interferents, the SNR that enable to accurately measure the target, the selectivity and the sensitivity of the method, signal stability, signal strength, etc. The environmental conditions measurements are aimed at enhancing the optimization of the multi-sensor technology parameters since a target could be engaged to be cluttered under variable weather conditions.

It is important to know that all pulsed-laser-based spectrometric methods (e.g., Raman spectroscopy) are suitable for LiDAR [1]. These authors refer that none laser-based technologies reviewed in their study is currently ready for deployment or being a functioning prototype.

3.1.1. MILLIMETER WAVES (MM-WAVES)

MM-waves range from 30-300 GHz (i.e. from 10 to 1mm, respectively) is capable to give both spectral and imaging information. [2] make use of a commercial Advanced Imaging Technology (AIT system) consisting of arrays of mm-waves antennas to get holographic images and identify anomalies therein that may represent threats. This holographic threat image can provide spectral data which can be used for identifying of threat composition by yielding the dielectric constant (as a function of frequency) of it. In this sense, we would make use of the current literature in this field to assess the more suitable technology within the scope of mm-waves sensing. See [3] for detection of concealed threats in this region. In order to support the complementarity of this technology to that of THz, is the absence of spectral signatures from threats in the MM-waves that are present in the THz frequencies [4].

3.1.2. TERAHERTZ (THZ)

THz —0.1 mm (3 THz) to 1 mm (0.3 THz), i.e. ranging from IR to MW, respectively, can span to sub-millimeter if extends up to roughly 3 mm (0.1 THz)—systems have roughly 10 times better spatial resolution w.r.t. those of MM-waves, and can be used as an excellent non-invasive complement of imaging or spectroscopic-based technology (such as LiDAR, Raman, or LIBS) to address the complexity of the signature environment provided by them and verify the presence of a suspicious threat. The emerging paradigm from the gap spectrum from THz frequency range involves both imaging and spectroscopic capabilities [5] (e.g., in concealed weapon detection), i.e. a THz image can be spectroscopically analyzed, and probe non-metallic and non-polar mediums. Unlike metals and water, [3] show that potential barriers such as cloth, paper, and plastics are semi-transparent to THz and have not observed significant confusion with explosive spectral features. Constituents in the detection of explosives-containing of threat-objects are mostly Nitra-mines (RDX, HMX), Nitric esters (PENT), and Nitro-compounds (TNT, DNT), which show fingerprint spectra of lines within the THz region ([6], [7], [8]), even upon concealed.

3.1.3. RAMAN SPECTROSCOPY

Raman is a high specificity molecular analysis technology and a non-destructive tool, capable of revealing concealed contents. Because of the weak scattering light measured from Raman instruments, it is necessary to collect as much light as possible to accomplish good quality observations. In this sense, a heterodyne spectrometer device can be attached.

- **Light Detection and Ranging (LiDAR):** LiDAR is an active remote sensing technology— i.e. a radar-like principle but applied mostly in the vis/IR region— able to monitor as mobile and static terrestrial, and airborne-based as well. It measures the differences in laser return times (backscatter signals) and the signal frequencies provide a target map-digital image and information about material composition from the properties of the backscatter signal. Because of the small focus diameter of the beam laser along with the high pulse repetition rate, LiDAR is able to see through masking items such as camouflaged mesh or leaves. Since a time ago, LiDAR has been used to monitor insects, features/objects buried, atmospheric composition, explosive compounds (even as trace amounts) due to the vapor pressure of the explosive, and so on. Furthermore, it is able to make fusion with different sensors. Raman-LiDAR has two components: transmitter (pulsed laser) and receiver (collect the backscattered light from the target) both are placed at the same end as coaxial modules. Raman-LiDAR allow to make a horizontal and vertical distribution and can measure at day and night, and also may be on-board/ground-based system. Raman-LiDAR [13] uses Raman scattering effect— i.e. the inelastic scattering of light by components with frequency shift features as a function of the distance— in the UV-IR regions, thereby a pulse laser light (from LiDAR system) is emitted to directly illuminate the threat-target and measure the reflected backscattered signal (i.e. back to the direction of the laser) and, finally, ends-up creating a map of the monitored target. LiDAR can target a wide range of materials, such as: non-metallic objects, rocks, chemical compounds, rein, aerosols, clouds, single molecules [13]. Hence, LiDAR is a useful technique to map physical/geological/atmospheric features, because of a combination of laser beam from LIDAR may generate a remote mapping of chemical contents. Note that LiDAR longer wavelength lasers may supply the metal barrier sensing and see-through it the objects beneath.

- **Laser-Induced Breakdown Spectroscopy (LIBS):** LIBS is a high sensitivity elemental analysis technology that consist of a high enough energy to break down the sample into plasma, which provides signals of emission lines with different time evolution (depending on the explosive-compounds) ranging from UV-vis-NIR spectral region. LIBS has a wide capability for chemical analysis —regardless of a sample solid, liquid, or gas. Due to the invasiveness of the technique (e.g., lasers by eye-safety concerns), tuning into this technique upon the multi-sensor operates is an underlying condition once the target-threat is identified. LIBS technology is field portable, and all its components can be miniaturized. This technology is able to mostly detect plastic and metal casing, whatever explosive target-material through tracking its elemental composition [10]. Raman-LIBS is able to offer complementary information about molecular and elemental composition of the threat for uncovering a concealed device in the surroundings that represents the conflict zone. Besides other more limited technology, [1] have tested LIBS and Raman spectroscopy outside the lab.
- **Hyperspectral imaging (HSI):** is an important technology widely used to the detection of surface and buried landmines from airborne platform [11]. Hyperspectral method consists of detecting anomalous variations in electromagnetic radiation reflected or emitted by threat-objects [12]. HSI data is able to geolocate, detect, classify and map the target through their spatial and spectral properties. Also, the hyperspectral sensor yields high spectral resolution and a large spatial cover. HSI-based surveillance systems for dynamic scenes with moving vehicles/objects and individuals, have proven its effectiveness to the detection of explosives [13]. [14] highlight the Raman-HSI and the laser-based technique LIBS extremely complementary spectroscopic techniques for standoff detection of explosives based on the SoA sensor data fusion.

3.2. DATA FUSION

In addition to get a high accuracy in a technique which leads to an increment in the spatial or spectral resolution, we may cover a long range of the long-waves domain by sweeping from the smaller wave-length of the IR-vis-UV region (e.g., LiDAR) compared to that of higher wave-length of the THz-MM-w region of the corresponding technique. The purpose of measuring synergic information aids to robustly detect in real-time not only smaller target-objects but also higher ones including a thorough spectroscopic data of the composition that supports the suspicious threat-material. In order to increase the probability of detection and recognition of the threat-target, we can draw upon the Bayesian fusion [15]. Because of all these are active sensors, it can also retrieve information during both day and night-time. Furthermore, active sensors could be weather independent as a function of wave-length. Note that high pulse repetition from laser-based instrumentation allows to accurately detect small objects. The exposed laser-based and imaging-based techniques are able to be upgradeable to new threats although all of them already needs more detailed studies about threat-targets to discern from the non-target.

A combination of imaging/spectroscopy technologies —equipped with different sensors— entails to a rigorous data acquisition during the process that depends on the software system, and the data analysis through strategies of data fusion along with Artificial Intelligent (AI) are the tools par excellence to address the issue. Integration of several technologies enables to get a more reliable response. Data fusion using any data correlation method such as machine-learning algorithms and other methods of matches or mismatches target identification may assist in the identification of the increasingly threat complex environment that appear as new and improved in the battlefield.

4. FURTHER SCOPE OF THE PROTOTYPE

This proposal should help to improve the diagnostic about the applicability of the threat detection technologies at ranged in advance to prevent attacks from the opposing forces, which would warrant a further study that would contribute to their development and deployment feasibly. Also, it might be used for forensic investigations of destructive explosive events. The further development of the prototype would involve an interdisciplinary effort that would make use of software tools that simultaneously simulate the data collected from the multi-sensor by tuning the interconnected elements that make it up when it is required to allow the remotely operated device to be able to distinguish harmless from threat-targets.

A comprehensive selected range of frequency from diverse technologies tracking for threat-targets and working in tandem by a remote operator located in a platform could lead to a further prototype that would be based on techniques that would be tested in realistic settings.

The results from the prototype will show the operator a real-time image that points out the probable threat to be evaluated. The network mode mentioned above by sweeping the highest conflict area as possible could be the cornerstone that greatly improves the critical decision making. The dissimilarities and tradeoffs between the desirable criteria of each technology will make this withstand prototype reliable and feasible.

For a full functionality prototype manufacturing, we would focus on combining the exposed techniques in this document to boost the performance of the overall system by simultaneous identification of multiple threat-targets in the field. In order to probe the prototype we would drive the investigation though an attempt to conceal the threat-targets by concealing them in target-materials, including clothing, camouflaged netting, soils, trees, vehicles, explosives beneath, and other targets-like.

5. CONCLUSIONS

This outlined project is an upgrade of the existing technology with the purpose of powering their strengths based on data from referenced bibliography and essential subjective valuation from the scientific background of the involved technologies that most fit to the threat detection scenario in the military field. Under the assessment of the exposed premises to carry out the proposed work along this document, stringent testing of the selected sensor technologies as most effective for the concerned purpose in this project will be undertaken to shed light to a sizeable research hot spot that could gain widespread acceptance by its use as ranged sensing of ground-truth threat-targets in a warfare context. Concept wise, this document represents a roadmap tended at fostering a fruitful way forward development undertaken of technologies susceptible of being used within TelLOS.

Intrinsically, the fact that no matter how critical a conflict scenario is because there is a ground-breaking instrument sweeping it at remote from a complete frequency view and which is targeted towards prevent an attack action from the enemies in there, foster a fruitful proposal forward.

The foremost intention is to save lives and assess how to enhance the field operations to protect the land forces preventing the advance of the front just by tracking the hazards.

References

[1] S. Wallin, et al., «Laser-based standoff detection of explosives: a critical review,» Anal Bioanal Chem, vol. 395, nº 2, pp. 259-274, 2009.

[2] Weatherall, J. C., et al., «The Identification of Explosives in Millimeter-Wave Imaging Systems,» Passive and Active Millimeter-Wave Imaging XXI, vol. 10634, pp. 78-84, 2018.

[3] M. Kemp, «Millimetre wave and terahertz technology for detection of concealed threats-a review.,» IEEE (Joint 32nd International Conference on Infrared and Millimeter Waves and the 15th International Conference on Terahertz), pp. 647-648, 2007.

[4] J.F. Federici, et al., «THz imaging and sensing for security applications—explosives, weapons and drugs,» Semicond. Sci. Technol., vol. 20, p. S266–S280, 2005.

[5] L.M. Narlagiri, et al., «Recent Trends in Laser-based Standoff Detection of Hazardous Molecule,» TrAC Trends in Analytical Chemistry, vol. 153, p. 116645, 2022.

[6] Pierno L., et al., «THz-TDS analysis of hidden explosives for Homeland Security scenarios,» IEE (6th Millimeter Waves and THz Technology Workshop), pp. 1-2, 2013.

[7] M.C. Kemp, et al., «Security applications of terahertz technology,» Terahertz for Military and Security Applications, vol. 5070, pp. 1-9, 2013.

[8] F. D. Lucia, Spectroscopy in the Terahertz Spectral Region, Springer Berlin Heidelberg, 2003.

[9] Y. Dwivedi, Concept and applications of standoff Raman spectroscopy techniques. Molecular and laser spectroscopy, Elsevier, 2020.

[10] Gottfried, J. L., et al., «Laser-induced breakdown spectroscopy for detection of explosives residues: a review of recent advances, challenges, and future prospects.,» Analytical and bioanalytical chemistry, vol. 395, pp. 283-300, 2009.

[11] E. M. Winter, «Detection of surface mines using hyperspectral sensors,» IEEE International Geoscience and Remote Sensing Symp., vol. 3, pp. 1597-1600, 2004.

[12] MacDonald, J., et al., Alternatives for landmine detection, Santa Monica, CA: Rand, 2003.

[13] Kütük, M., et al., «Ground-based Hyperspectral Image Surveillance System for Explosive Detection: Methods, Experiments, and Comparisons,» IEEE Journal of Selected Topics in Appl. Earth Obs. and Remote Sensing, vol. 16, pp. 8747-8763, 2023.

[14] Wentworth, R. M., et al., «Standoff Raman hyperspectral imaging detection of explosives,» IEEE Antennas and Propagation Soc. Intern. Symp., pp. 4925-4928, 2007.

[15] Miziolek, A., et al., «A new standoff CB detection technology based on the fusion of LIBS and Raman,» CBD PS & T Conference, pp. 17-21, 2008.

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AI-GENERATED THREATS TO MARITIME NAVIGATION USING DECEPTIVE ISAR IMAGES

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Abstract

Radar systems are one of the main elements of ship navigational chains to provide vital information on the surrounding area in terms of distance and speed. However, they also expose vulnerabilities to cyber threats, particularly through the manipulation of radar data to potentially compromising the navigational system. This paper focuses on the generation of fake radar images, specifically in Inverse Synthetic Aperture Radar (ISAR) systems, which closely resemble real targets and pose significant risks to maritime operations. This can be achieved using advanced artificial intelligence models like Generative Adversarial Networks (GANs). Real data analysis in this paper has been conducted on an ISAR database of an Italian ship extracted from the NATO SET-196 trials conducted in 2014, which demonstrates the capability of GANs to create convincing fake ISAR image. Such an experiment raises awareness of the vulnerability of imaging radar systems to cyber-attacks.

Keywords

Cyber-attacks, Maritime Navigation, Inverse Synthetic Aperture Radar (ISAR), Generative Adversarial Networks (GANs), Advanced Persistent Threats (APT)

1. INTRODUCTION

Radar systems are essential for ship navigation, as they provide information about the surrounding area, such as the distance (range) and speed (Doppler) of other ships. However, they may also open the door for cyber threats. Data manipulation based on vulnerabilities of radar systems can potentially cause navigational problems, such as collisions, deviations, or delays, specifically by the creation of fake radar images. These fake images are not like simple noise or interference, but they are realistic targets that do not exist or have been modified. Unlike traditional techniques, such as jamming or spoofing, these fake images are often generated using advanced artificial intelligence models, such as Generative Adversarial Networks (GANs), which can learn from the surrounding area to create high-quality fake data. By these fake images, an imaging radar system can be possibly fooled when the size or position of a ship is modified, or a new ship or object is synthetically added.

Synthetic Aperture Radar (SAR) and Inverse Synthetic Aperture Radar (ISAR) are widely used in different remote sensing applications, particularly surveillance and reconnaissance, due to their capacity in forming high resolution radar images in all-weather conditions. Both techniques rely on the relative motion between the target and the radar to create a synthetic aperture, however, the source of this relative motion differs. In SAR, the radar is mounted on an airborne or spaceborne platform to capture the image of a stationary target. Whereas, in ISAR, the target, such as a ship, is moving in a non-cooperative manner and changes its orientation with respect to the radar. The target's motion is used to create the synthetic aperture effect and form the image of the target. Note that target's motion in ISAR is not controlled by the radar, but by the target itself, and this makes it possible to inject convincing fake images into the imaging chain

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of ISAR systems. Therefore, an attacker could use this uncertainty and create fake images that match the expected motion of the target. For example, an attacker could create a fake image of a ship that seems to get close to the radar or a friendly ship that is an enemy ship indeed. This capability highlights a substantial risk, since an attacker could create deceptive navigational hazards or mask real threats, endangering the security of maritime operations. This vulnerability is particularly concerning in the context of Advanced Persistent Threats (APTs). APTs are sophisticated, long-term cyberattacks carried out by highly skilled actors, often with state backing. These attackers possess the resources and expertise to exploit vulnerabilities in complex systems like maritime radar and use them for malicious purposes. APTs are not random attacks, but carefully planned and designed to penetrate a specific organization, evade existing security measures, and remain undetected for a significant period.

This paper investigates the feasibility of generating credible ISAR images using GANs. GANs are a type of artificial neural network that can learn from real data and produce synthetic data that are indistinguishable from the real ones. We use GANs to generate fake ISAR images that mimic the characteristics of real ISAR images, such as resolution, contrast, noise, and motion. Through this research, we aim to investigate new dimensions of cybersecurity in the maritime domain, and to raise preparedness for the potential threats posed by fake ISAR images.

The reminder of this paper is organized as follows. In Section 2, we review the literature on the cybersecurity risk and the GAN-based radar image generation. Section 3 examines the cyber threat, while Section 4 describes the ISAR imaging and the framework that we suggest for the synthesis of fake images. In Section 5, we show the real data used for the experiment and the results obtained. Finally, in Section 6 we draw the conclusion.

2. LITERATURE REVIEW

This work is motivated by the possibility of an attacker injecting an APT into a naval radar system. Previous studies have already investigated the potential for exploiting vulnerabilities in networking protocols, but this research focuses on a different threat: the attacker's ability to manipulate the radar's internal processing to inject fake (ISAR) images. In our recent work [1], we have investigated potential cyber-attack entry points in a software designed radar system that cyber attackers could exploit. These fake images created using GANs for example could deceive the crew by presenting misleading information about surrounding objects or even hiding real threats altogether. Balz et al. [2] compare three recent SAR simulators, including RaySAR[3], CohRaS [4] and SARViz[5], which are integrated SAR image simulators meaning that they do not provide raw signal data but directly simulate SAR images. RaySAR and CohRaS are two ray tracing-based SAR image simulators. SARViz, is a real-time SAR simulator based on the rasterization. It is noteworthy that using accurate computer-aided design (CAD) models for each target in SAR scenes is not practical because the scenes are very large and have targets that do not cooperate.

Therefore, Guo et al. [6] proposed an end-to-end GAN, to directly synthesize SAR images from the known image database. They have mentioned that the training process of GAN models was difficult, especially for SAR images which are usually affected by noise interference so that they proposed a clutter normalization method alleviate them. Zhou et al. [7] made an ISAR simulation imagery dataset using the bidirectional analytic ray tracing (BART), which is an electromagnetic scattering calculation tool [8]. By leveraging BART, they generated 2160 ISAR image crops of moving aerial targets. Afterward, they employed a GAN-based ISAR image generation network to interpolate the images across different orientations, effectively increasing the number of training samples. Despite being trained on a limited ISAR image dataset, the generative network successfully generates a significant number of ISAR images with varying orientations for aerial targets. To improve training stability, Zheng et al. [9] employed multiple discriminators in their proposed GAN. Sun et al. [9][10] proposed an attribute-guided GAN for few-shot SAR image generation. Mao et al. [11] proposed constrained naive GAN in SAR-ATR to boost the low signal-to-clutter-noise ratio. Zeng et al. [12] mentioned that the problem with most existing GAN-based methods is that they cannot confirm what features the generator learns, thus they struggle in generating precise SAR target images. They proposed an angle transformation GAN to generate azimuth-controllable SAR target images while preserving the target details.

3. THE CYBER THREAT

Establishing a strong "cyber resilience" culture in the defence sector, particularly for radar systems, is imperative. This entails embedding cyber resilience throughout the entire project lifecycle, starting from the initial design phase. Collaboration among all project teams, not solely specialized security teams, is crucial to ensure that security is an integral part of the development process rather than an afterthought. APTs pose significant challenges to modern radar systems, often targeting processing units as potential entry points. They exploit vulnerabilities in reconfigurable computing units like Field- Programmable Gate Arrays (FPGAs) since their flexible nature can accept inputs that's difficult to detect using traditional security measures. Furthermore, malicious actors could potentially utilize AI-powered tools to create fake, yet highly realistic, data, in our case ISAR images. By injecting these fabricated images into the processing chain, attackers could manipulate the radar's perception of the surrounding environment, potentially leading to missed threats, false positives, or disrupted operations. This emerging threat highlights the importance of not only securing hardware itself but also developing robust algorithms to detect and mitigate such sophisticated attacks within the signal processing chain.

4. METHODS AND MATERIALS

4.1. ISAR IMAGING

Inverse synthetic aperture radar (ISAR) is a proven radar imaging system to capture 2D radar images of a non-cooperative target. It achieves high resolutions in both range and cross-range dimensions using wideband pulses and coherent integrations in different angles, respectively. Note that, unlike range resolution, which is primarily determined by used bandwidth, cross-range resolution in ISAR is not a fixed (known) parameter and is dependent on the motions of the target, particularly, how much the target's orientation changes during the observation time, as shown in Figure 2. The greater the variation, the finer the cross-range detail captured in the image. There are many algorithms to reconstruct an ISAR image from the received echoes.

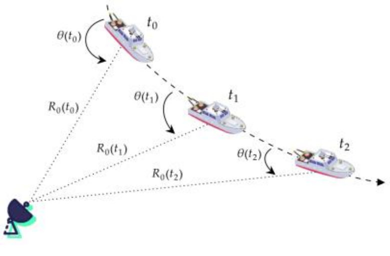


Figure 2 Target's orientation changes during the observation time.

Two common ISAR reconstruction algorithms are range-Doppler (RD) and Back Projection (BP) [13]. RD is the simplest and most fundamental method. It is based on applying a 2D Inverse Fourier Transform to the received signal after compensating for the target's motion. In RD, it is assumed that target rotation is relatively constant during observation, which is not always true in a real-world scenario. The point spread function (PSF), the image of an ideal hypothetical needle-shaped target located at arbitrary location x, can be formed by

$$\omega(x_1, x_2) = K sinc(x_1/\delta_{x_1}) sinc(x_2/\delta_{x_2}) \qquad (1)$$

where

$$\delta_{x_1} = \frac{c}{2 f_0 \Omega_{eff} \Delta t} \qquad (2)$$

$$\delta_{x_2} = \frac{c}{2B} \qquad (3)$$

Note that c is the speed of light, f_0 is the carrier frequency, Ω_{eff} is the effective rotation vector, Δt is the observation time, and B is the bandwidth of the transmitted signal [14]. On the other hand, BP provides the most accurate image reconstruction but requires more processing power. BP needs prior knowledge of the target's motion to create the matched filter. Additionally, the calculations for each pixel in the image make it computationally expensive. Before applying the reconstruction algorithms, a process called autofocusing is typically performed. Autofocusing aims at compensating the errors in the target's motion estimation to make it sharper. Some of the well-known autofocusing methods are Image Contrast Based Autofocus (ICBA) [15], which is a parametric method based on maximization of the image contrast, IEBA, which is similar to ICBA but uses the concept of image entropy, Dominant Scatterer Autofocus (DSA) [16], which is based on time-delay estimation and beamforming, and Phase Gradient Algorithm (PGA) [17], which is like DSA but uses a Maximum Likelihood estimation [14].

4.2. GENERATIVE ADVERSARIAL NETWORK (GAN)

The basic architecture of a GAN is illustrated in Figure 3 [18]. where two neural networks, in our case two convolutional neural networks, namely, the Generator and the Discriminator, compete against each other. The Generator G aims at generating fake data, in our case ISAR images, that are indistinguishable from the real ones. On the other hand, the Discriminator D tries to differentiate between the fake and real images. Generator takes noise z as input to create fake images. These fake images, along with real images are then fed to the Discriminator. Subsequently, the Discriminator generates a binary output where 1 signifies the image is real and 0 indicates that the image is fake. The backpropagation based adversarial training is in fact a minimax game problem with two players, namely, D and G, where D tries to maximize V while G tries to minimize it.

$$\min_G \max_D V(D, G) = \mathbb{E}\,[\log(D(x))] + \mathbb{E}[\log(1 - D(G(z)))] \qquad (4)$$

In other words, D is trained to maximize the probability of assigning the correct label to both training examples and samples from G. Simultaneously, G is trained to minimize log(1 − D(G(z))) [19].

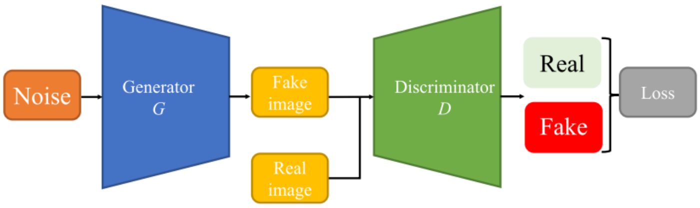
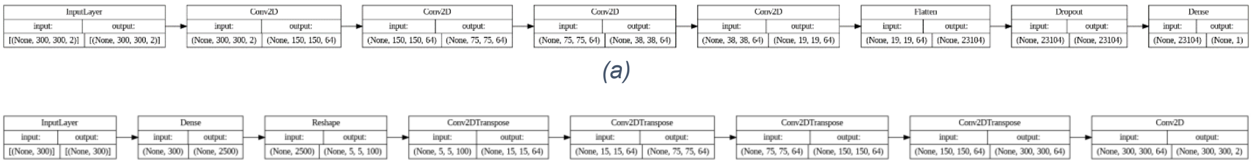


Figure 3 The basic block-diagram of a GAN [18]

4.3. THE PROPOSED METHOD

Let's begin with the Generator. We have empirically determined the size of the latent domain (the space from which random input vectors are generated) to be 300 neurons. This is unrelated to the generator's output shape, which is (300, 300, 2), representing an image with 300 by 300 pixels and two channels (real and imaginary components). A single fully connected layer, followed by a LeakyReLU activation function, is used, and then reshaped into a 3D tensor with dimensions of (5, 5, 10), i.e., a height of 5, a width of 5, and 10 channels. This configuration is more suitable for subsequent deconvolutional layers. Four deconvolutional layers are utilized to progressively upsample the feature maps. Specifically, the first layer employs strides of (3, 3) to increase the feature map size by a factor of three in both height and width, resulting in a new shape of (15, 15, 64). The resolution is then sequentially increased to (75, 75, 64), (150, 150, 64), and finally (300, 300, 64). All deconvolutional filters generate 64 feature maps using a (3x3) kernel and are followed by a LeakyReLU activation function. Ultimately, a convolutional filter reduces the number of feature maps from 64 to 2 without altering the spatial dimensions, resulting in the generator's output size of (300, 300, 2). The generator's output is scaled to a range of -1 to 1 using a tanh activation function.

The Discriminator takes a complex matrix with a shape of (300, 300, 2) as input. Four convolutional filters followed by LeakyReLU activation functions are employed to extract the main features from the input. Each convolutional filter has a stride of (2, 2), which effectively downsamples the input feature map by a factor of 2 in both the height and width dimensions. The final multi-dimensional feature map is flattened into a one-dimensional vector. A Dropout layer is then applied to prevent overfitting by randomly dropping a certain percentage of neurons during training. Finally, the learned features are fed into a fully connected layer with only a single neuron to distinguish between fake and real instances. The architectures of the Generator and Discriminator are shown in Figure 4 (a) and (b), respectively.



(a)

(b)

Figure 4 The architectures of (a) the Generator and (b) the Discriminator.

The discriminator is trained using the binary cross-entropy loss function and the stochastic gradient descent optimization method with mini-batches. It is common practice to update the discriminator with separate mini-batches of real and fake images, rather than combining them into a single batch [20]. The generator is trained by updating the combined model with noise, ensuring that only the generator's weights are updated, as the discriminator's weights remain frozen [21]. Furthermore, when training the generator within the combined model, the objective is to deceive the discriminator; therefore, we assign inverted labels for the fake data (indicating they are real).

5. REAL DATA ANALYSIS

5.1. DATASET

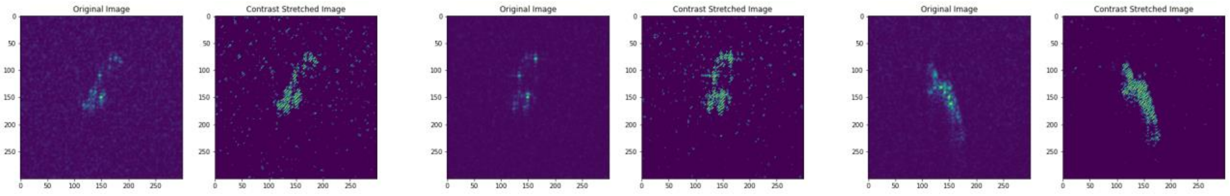
In this work, we analyzed the radar data from the NATO SET-196 trials conducted in 2014 at the Istituto Vallauri in Livorno, Italy, with detailed information in [22]. The data collection was performed by using an X band ground-based linear frequency-modulated continuous wave radar, namely Pisar Radar (PIRAD), which is designed for ship traffic monitoring in harbours. This radar works at the carrier frequency of 10.7 GHz with 300 MHz bandwidth. A notable subject of these trials was the Astice A5379, a training ship from the Italian Naval Academy. The ship's dimensions are 33.25 meters in length, 6.47 meters in width, and 12 meters in height, with a top speed capability of 12 knots. This ship was chosen as the main point for the experiment discussed in this paper. Illustrations of the experimental arrangement and the ship are provided in Figure 5 (a) – (c). The training set for our GAN consisted exclusively of ISAR images of Astice ship derived from the raw data. To isolate the Astice as the only target in the image, we employed a tracking algorithm in conjunction with data from the onboard Inertial Measurement Unit (IMU). We first generated the range-Doppler plot of the received data, since it is the most widely used plot for the radar operators to detect and track vessels. Figure 5 (d) shows a sample range-Doppler map. After extracting the area of interest. i.e., relevant to Astice A5379, the final ISAR image was then reconstructed using the ICBA technique.

Figure 5 (a) PIRAD system, (b) NATO-SET-196 trials (c) the Astice A5379, (d) a range-Doppler map

Three ISAR images used in the training dataset of the GAN are shown in Figure 6. For a better visualization, we have also illustrated a contrast stretched version of each image next to it, however the original images are used to train the GAN. Contrast stretching is applied to real and imaginary part separately, by normalizing each pixel value (I) to low (L) and high (H) intensities cutoff by

$$I_{s,real} = \frac{I_{real} - L_{real}}{H_{real} - L_{real}} \quad , \qquad I_{s,imag} = \frac{I_{imag} - L_{imag}}{H_{imag} - L_{imag}} \qquad (5)$$

where L and H have been empirically set to 98% and 99% of the intensity values.

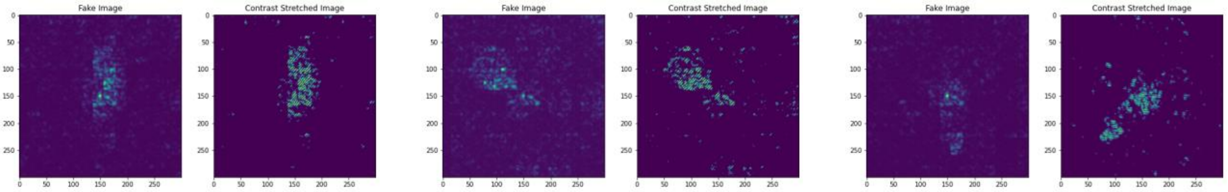


(a) (b) (c)

Figure 6 Three ISAR images of Astice A5379 together with their contrast enhanced versions for better visualization.

5.2. GENERATED IMAGES

Similar to the previous part, Figure 7 shows three images generated by our proposed GAN architecture. Note that the contrast-stretched versions are included solely for improved visualization purposes and are not actual outputs of the GAN. Additionally, while the GAN generates complex-valued outputs, only the magnitude is displayed in Figure 6 and Figure 7.



(a) (b) (c)

Figure 7 Three generated ISAR images of Astice A5379 together with their contrast enhanced versions for better visualization.

Our observations from the generated images, particularly the contrast-stretched versions, implies that our GAN effectively captured high-frequency details. These details appear as small stripes within the images. However, to quantify the performance of the GAN, we measure some metrics to understand the fidelity of the fake images to the original ones. First, we have depicted the density of pixel values in original and fake images in Figure 8. It should be noted that the training data and generated data have both two channels (complex-valued), normalized from 1 to 1, and the density is shown for all values, not the magnitude. We can see that generated images follow a somewhat similar distribution in pixel intensity as the original images.

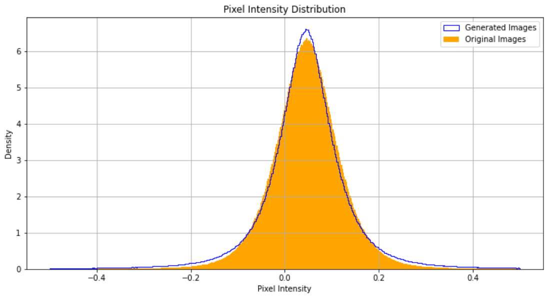
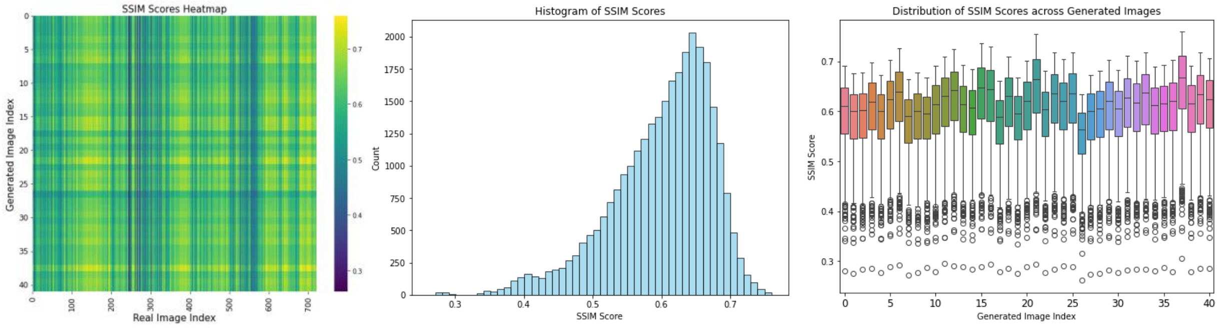


Figure 8 Density of the pixel values (both real and imaginary values normalized to -1 to 1) in the real and fake images

Next, we calculate the SSIM (Structural Similarity Index Measure) [23] metric between 40 generated (fake) images and all 720 training images (real). SSIM is based on three comparisons between two images, luminance, contrast, and structure, and the output value is the weighted combination of the aforementioned parameters. The heatmap of these measurements is visualized in Figure 9 (a). By taking all values into account, the histogram of SSIM can be visualized in Figure 9 (b), which is has the following features: Mean SSIM: 0.6008, Median SSIM: 0.6146, and Standard Deviation of SSIM: 0.0726. Furthermore, for each generated image, we can depict the SSIM distribution with respect to all the original images within the training dataset, shown in the box and whisker plot of Figure 9 (c). It's noticeable that the lower and upper quartiles of SSIM in most generated images are around 0.6 ± 0.05, indicating the consistency in similarity across different pairs of generated and original images.



(a) *(b)* *(c)*

Figure 9 SSIM metric between each generated image and each original image: (a) Heatmap, (b) Histogram of all values, (c) distribution across generated images.

Our research finding is focused on generating fake ISAR images, yet it should be acknowledged the following constraints. Firstly, to effectively train a GAN, a substantial number of ISAR images of different targets is needed. However, our experiment was limited to images of a single ship. To have a more robust system, we should include different targets with different shapes, sizes, and radar cross-section characteristics. This diversity helps the GAN to better generalize and create high-fidelity fake images. Secondly, in ISAR systems, the geometry of the target and its relative motion to the radar are very important. The target motion, like rotation and translation, change the image drastically. Thirdly, the quality of the ISAR images depends also on the parameters of the radar system, such as frequency bandwidth, which dictates the range resolution of the images. Lastly, the environmental factors such as atmospheric conditions, clutter, and interference can also affect image quality.

6. CONCLUSION

This study has focused on the potential cybersecurity threats posed by synthetic ISAR imagery, particularly within the maritime domain. Our research has not only assessed the feasibility of generating credible ISAR images using GANs but has also highlighted the urgent need for preparedness against such cyber threats. The synthetic ISAR images created by GANs, which closely resemble real images in resolution, contrast, and noise, simply imply the need for robust detection and mitigation strategies. Future research direction in this field can explore the use of data augmentation techniques to enrich the diversity of the training dataset, use of conditional GANs to generate more realistic images, and devising effective post-processing algorithms to further refine the quality of fake images.

References

[1] G. Meucci, B. Karahoda, A H. Oveis, F. Mancuso, E. Jajaga, A. Cantelli-Forti, “Naval Cybersecurity in the Age of AI: deceptive ISAR Images Generation with GANs,” 48th IEEE Conference on Local Computer Networks (LCN), 2023.

[2] T. Balz, H. Hammer, and S. Auer, “Potentials and limitations of SAR image simulators - A comparative study of three simulation approaches,” ISPRS J. Photogramm. Remote Sens., vol. 101, pp. 102–109, 2015

[3] S. J. Auer, "3D synthetic aperture radar simulation for interpreting complex urban reflection scenarios", 2011.

[4] H. Hammer and K. Schulz, "Coherent simulation of SAR images", Proc. SPIE, vol. 7477, pp. 74771G-1-74771G-9, Sep. 2009.

[5] T. Balz and U. Stilla, "Hybrid GPU-based Single- and double-bounce SAR simulation", IEEE Trans. Geosci. Remote Sens., vol. 47, no. 10, pp. 3519-3529, Oct. 2009.

[6] J. Guo, B. Lei, C. Ding and Y. Zhang, "Synthetic aperture radar image synthesis by using generative adversarial nets", IEEE Geosci. Remote Sens. Lett., vol. 14, no. 7, pp. 1111-1115, Jul. 2017.

[7] R. Zhou, Z. Yang, and F. Wang, “ISAR images generation via generative adversarial networks,” Proc. IEEE Int. Geosci. Remote Sens. Symp., pp. 5267–5270, 2021.

[8] F. Xu and Y.Q. Jin, “Bidirectional analytic ray tracing for fast computation of composite scattering from electric-large target over a randomly rough surface,” IEEE Trans. Antennas Propag., vol. 57, no. 5, pp. 1495– 1505, May 2009.

[9] C. Zheng, X. Jiang, and X. Liu, “Semi-supervised SAR ATR via multidiscriminator generative adversarial network,” IEEE Sensors J., vol. 19, no. 17, p. 7525–7533, 2019.

[10] Y. Sun et al., "Attribute-guided generative adversarial network with improved episode training strategy for few-shot SAR image generation", IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens., vol. 16, pp. 1785-1801, 2023.

[11] C. Mao, L. Huang, Y. Xiao, F. He and Y. Liu, "Target recognition of SAR image based on CN-GAN and CNN in complex environment", IEEE Access, vol. 9, pp. 39608-39617, 2021.

[12] Z. Zeng, et al. "ATGAN: A SAR Target Image Generation Method for Automatic Target Recognition." IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (2024).

[13] R. Vehmas and N. Neuberger, "Inverse synthetic aperture radar imaging: A historical perspective and state-of-the-art survey", IEEE Access, vol. 9, pp. 113,917-113,943, 2021.

[14] M. Martorella, ‘‘Introduction to inverse synthetic aperture radar,’’ in Academic Press Library in Signal Processing, vol. 2. Amsterdam, The Netherlands: Elsevier, 2014, pp. 987–1042.

[15] M. Martorella, F. Berizzi, B. Haywood, A contrast maximization based technique for 2D ISAR autofocusing, IEE Proc. Radar Sonar Navig. 152 (4) (2005) 253–262

[16] B. Haywood, R.J. Evans, Motion compensation for ISAR imaging, in: Proceedings of ASSPA 89, Adelaide, Australia, 1989, pp. 113–117.

[17] C.V. Jakowatz, D.E. Wahl, P.H. Eichel, D.C. Ghiglia, Spotlight-Mode Synthetic Aperture Radar: A Signal Processing Approach, Springer, 1996.

[18] J. Zhang et al., "Application of deep generative networks for SAR/ISAR: A review", Artif. Intell. Rev., vol. 56, no. 10, pp. 11,905-11,983, 2023.

[19] I. Goodfellow et al., "Generative adversarial nets", Proc. Int. Conf. Neural Inf. Process. Syst., pp. 2672-2680, 2014.

[20] J. Brownlee, Generative Adversarial Networks With Python: Deep Learning Generative Models for Image Synthesis and Image Translation, Vermont, VIC, Australia: Machine Learning Mastery, 2019.

[21] D. Foster, “Generative deep learning: teaching machines to paint,” Write, Compose, and Play (Japanese Version) O’Reilly Media Incorporated, pp. 139-140, 2019

[22] “Multi-Channel/Multi-Static Radar Imaging of Non-Cooperative Targets,” 2017, accessed: 2023-05-24. [Online]. Available: https://www.sto.nato.int/publications/ STO%20Technical%20Reports/Forms/All%20Documents.aspx

[23] Z. Wang, A. Bovik, H. Sheikh et al., “Image quality assessment: from error visibility to structural similarity,” IEEE Trans. on Imag. Proc., vol. 13, no. 4, pp. 600 – 612, April 2004

ENHANCING MILITARY HELICOPTER OPERATION: A STUDY ON BALLISTIC IMPACT DAMAGE DETECTION

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Abstract

The success of military mission heavily depends on the integrity and reliability of systems and structures in operation. Integrating adaptable online damage detection systems for real-time structural and system integrity assessment plays a crucial role in the future mission success, allowing for cost-effective, efficient, and sustainable solutions. In this framework, algorithms based on artificial intelligence can be used to understand the dynamic behaviour of the monitored system, potentially isolating damage features from confounding influences, typical of a harsh operational environment. This paper introduces a method using ML, specifically a nonlinear autoregressive with exogenous inputs (NARX) model, to allow for ballistic impact detection on the tail rotor slant shaft of a helicopter. The NARX model analyzes substantial variations in acceleration signals from the transmission shaft before and after an impact, aiming to identify damage in view of structural integrity assessment, as an aid for decision making in operation. The proposed methodology is evaluated in the EDA Cat.B project SAMAS 2 - Structural health and ballistic impact monitoring and prognosis on a military helicopter - using experimental data from a rotating shaft with various ballistic impact damages, demonstrating effective detection performance and potential for assessment of damage severity.

Keywords

Military, Helicopters, Damage Detection, Machine Learning, Impact Damage.

1. INTRODUCTION

Over the last decade, the importance of the defence sector has increased significantly due to the unfolding conflicts on European borders and the global stage, impacting economic growth, critical infrastructures, and, most crucially, civilian well-being. Recognizing this complex situation, there is a need to prioritize reinforcement of security measures to guarantee the continuous operation of defence systems. This necessity has prompted the industry and academia to develop new methodologies and improve existing technologies, aiming to enhance the reliability and availability of military systems.

Military systems, including aircrafts, naval ships and armed vehicles operate globally in harsh environments, posing threats to their structural integrity and increasing the risk of system failures. Military helicopters, nowadays evolving into more intelligent and complex dynamic systems, are still susceptible to malfunctions, degradations, and damages **Error! Reference source not found.**. Primary helicopter structural components are typically inspected according to a scheduled maintenance plan to ensure their functionality. As an example, the tail rotor drive line (TRDL) can be prone to degradation (e.g. related to bearing degradation, wear and fatigue of gearbox components, shaft misalignments, etc.) manifesting as additional and/or different vibration signatures, potentially compromising the helicopter structural integrity in case of failure. For military helicopters, the occurrence of ballistic impact events poses additional threats to primary structural components, which would benefit from an immediate assessment of the

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structural condition for operation optimization, e.g. informing the crew on whether to land as soon as possible or practical or allowing for a return to base. Thus, real-time monitoring techniques offer solutions to optimize aircraft operations allowing for more informed decisions in critical situation.

Conventional methods for assessing structural damage rely on the analysis of numerical data derived from computer simulations and experimental data obtained through damage tests. While the credibility of these methods is generally high, significant limitations, such as substantial economic challenges and concerns regarding time efficiency, have been raised, and the increasing pressure toward a more environmentally sustainable defence framework demands for optimized solutions with limited logistic impact. In many cases, these methods cannot be directly implemented to detect damage in real-time and to alert the crew and ground control, posing a notable threat to mission reliability in case of primary system damage. To mitigate these issues, an effective measure involves integrating predictive tools into helicopters with a dual scope of delivering cost-efficient maintenance schedules and to monitor the operating system and its performance for mission optimization, with a view toward crew safety.

With this perspective, most recent military helicopters are nowadays equipped with a Health and Usage Monitoring System (HUMS), leveraging features extracted from sensor measures for system diagnosis and, in limited applications, prognosis, aiming the increased aircraft availability through enhanced maintenance planning. However, the current onboard HUMS lacks the capability to detect impact events and assess the potential structural damage, which poses a significant limitation in battlefield scenarios where rapid decision-making is vital for the integrity of the aircraft.

In this context, integrating artificial intelligence (AI) into HUMS has been a very active research topic since decades and militaries prominently utilize AI for managing cyber warfare, UAVs, autonomous weapons systems, and structural health monitoring (SHM) as well. In the latter, machine learning (ML), a subset of AI, processes time-series data to identify abnormal behaviors, ensuring the structural integrity of systems by anticipating potential risk of failures **Error! Reference source not found.**. Military helicopters utilize various sensors to continuously monitor and collect data on machinery performance. Data-driven approaches based on ML algorithms analyze this data to detect patterns and anomalies that may indicate potential failures or malfunctions. In the context of ballistic impact damage on rotating parts, studies have explored its effects on system dynamics **Error! Reference source not found.**, analyzing how the system vibrations are modified after an impact and trying to distinguish damage effect by other confounding influences. Before damage occurs, low-intensity vibrations result from imperfections like machining errors and misalignment. However, after a ballistic impact, eccentric loads on the rotor due to mass loss and stiffness asymmetry lead to increased system response and sub-harmonic resonance **Error! Reference source not found.**. HUMS can utilize vibration analysis in rotating machinery by monitoring its response with accelerometers **Error! Reference source not found.** and many applications have successfully employed vibration based SHM techniques to monitor the overall condition of various systems cost-effectively and reliably.

More specifically, among the ML methods, recurrent neural networks (RNNs) are a category of artificial neural networks with delayed feedback. RNNs excel in processing input and output signals from time-varying systems without prior knowledge of the structural system. A specific type of RNN is the series–parallel structure of the nonlinear autoregressive with exogenous inputs (NARX) network. The NARX network, typically a recurrent feedforward backpropagation multi-layer perceptron network that incorporates time-delayed feedback on the model's output, is widely employed for long-term machine state monitoring based on vibration data **Error! Reference source not found.**, proving to be successful in prediction of dynamic system evolution, thus potentially a promising candidate for damage detection in vibrating components.

This study proposes a monitoring tool designed for ballistic impact damage detection in military helicopters, aiming to enhance the operational capabilities through the integration of existing helicopter systems, like HUMS and sensor networks, and commercial off-the-shelf systems (i.e., accelerometers) and ML tools. The tool utilizes the NARX model to extract reliable diagnostic indicators, triggering an alarm based on significant alterations in vibration signals. Though being tested in presence of a ballistic impact damage scenario, the approach is valid for detection of various sources of degradation, mitigating the risk of unexpected events and their economic costs, eventually associated with the loss of the aircraft. If integrated into existing helicopter fleet monitoring systems, it is expected to improve the next generation of systems, promoting coordinated management and enhancing the operation (and safety) in both dual-use military and civilian applications **Error! Reference source not found.**.

The work is organized as follows. Section 2 presents the framework for damage detection and introduces the methodology. Section 3 shows the capabilities of the proposed method through an experimental case study involving the NARX model for damage identification. Finally, Section 4 draws out the conclusions from this work and presents possible further developments.

2. METHODOLOGY

The study introduces a data-driven method for identifying damage by employing the NARX model to estimate time series data collected from accelerometers during flight. As a basic principle, the estimation model uses the available observations generated from acquired vibration data to detect damage induced alterations. Firstly, the model is trained offline on a baseline to extract the underlying patterns of the system response at its pristine state. In the event of a ballistic impact, the estimation model aims to detect deviations from normal behaviour and trigger an alarm. The effectiveness of the model depends on its ability to differentiate between external influences causing anomalies in the time series and the effect of damage on vibration data, ensuring accurate damage detection. Here, the proposed methodology is assessed through a case study, that involves experimental data acquired before and after ballistics testing used to train and test the estimation model.

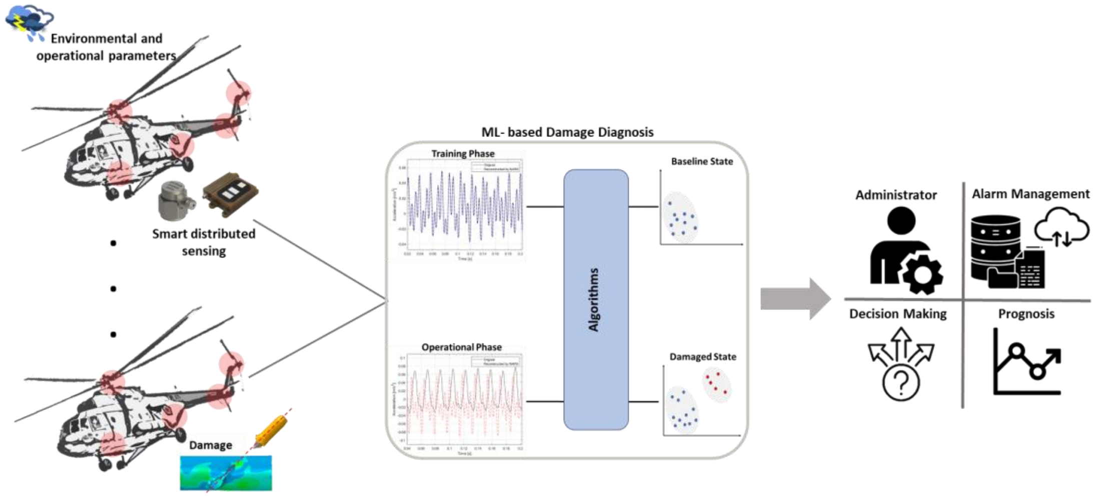

Figure 10. The methodology of the proposed ballistic impact damage detection tool.

2.1. ESTIMATION MODEL

NARX networks exhibit unique structural connections between nodes, and each node possesses memory to handle inputs from both the current state and interconnected nodes. The NARX model uses of past values of the output signal and past values of an independent input signal to estimate the response of a discrete nonlinear system (Figure 11). This estimation relies on an identified nonlinear function, approximated using a multilayer perceptron with sigmoidal activation functions. The discrepancy between the estimated output time series and the actual is termed as the estimation error described by a statistical distribution. Any change in the statistical distribution of the estimation error serves as a damage indicator and consequently as an alarm. In this work, the input signal comprises the acceleration response from the neighbour sensor, while the output signal contains the response from the master sensor. The Levenberg–Marquardt backpropagation algorithm was adopted for network training. Finally, the optimal values for the parameters and structure of the NARX model were obtained.

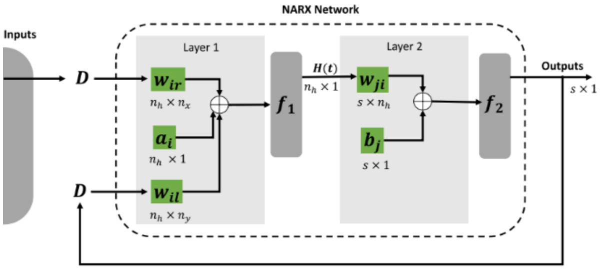

Figure 11. The structure of the NARX network

3. DAMAGE DETECTION

A dedicated series of dynamic tests has been conducted to establish a baseline representing the undamaged state of the system. In particular, 110 consecutive dynamic tests have been performed at the baseline condition, before the ballistics testing (Table 2). During these runs, five acquisitions were obtained to capture the environmental and operational effect on the vibration response of the structure, subsequently encoding them into the estimation models. In this study, we focus on acquisitions at the nominal speed ($\Omega = 3388\,rpm$) of the TRDL system, performed using both the Master and Neighbor accelerometers (Figure 12). These signals were used for training the estimation model. Specifically, the steady state of the acquired signals was chosen, with the transient phase excluded as it does not serve the purpose of damage detection. Then, each signal was offline filtered using a 10th-order band-pass finite impulse response (FIR) filter with a lower cut-off frequency of $120\,Hz$, while the resampling rate is $5000\,Hz$. The primary reason for filtering is to ensure that the time series contains valuable information regarding the system state by mitigating the effect of confounding influences on the performance of the estimation models. Finally, online damage detection is performed on 20 experimental signals obtained after ballistic testing of two different damage severities.

Table 2. Series of dynamic tests for various operational conditions before and after the ballistics tests.

	ID	n	Observations	Speed [rpm]	Torque [Nm]
Before ballistic test	BS $\#n$	65 runs	5/run	1800-3388	/
	TS $\#n$	28 runs	5/run	1800-3388	1.0-2.0
	MS $\#n$	27 runs	5/run	1800-3388	2.0
	R$\#n$ - BS	2 rotors	/	3388	/
	R$\#n$ - TS	2 rotors	/	3388	1.0-2.0
After ballistic test	PI BS$\#n$	10 runs	5/run	3388	/
	PI TS$\#n$	10 runs	5/run	3388	1.0-2.0
	PI R$\#n$ - BS	2 rotors	/	3388	/
	PI R$\#n$ - TS	2 rotors	/	3388	1.0-2.0

3.1. EXPERIMENTAL ACTIVITIES

A test rig was designed and manufactured to replicate the transmission line of a helicopter to test the proposed estimation model. The rotor is fabricated of aluminum alloy and firmly attached to supports on each side using five bolts. The driveline is primarily supported by four bearings, with accelerometers mounted to capture the vibrations generated during rotation at $3388rpm$, representative of the operational shaft's speed on the helicopter. The rotational velocity is provided by a three-phase electric motor (Saipee JM90La2B3) remotely controlled by a PC through the inverter (RS PRO, $2{,}2\,kW$ 3-phases, $380-480V$, $599Hz$) frequency regulation, forcing the system to follow the predefined speed profile. The installed accelerometers (PCB Piezotronics 333B30) capture accelerations up to $50g$ and operate at an acquisition frequency of $51{,}2kHz$. Signals acquired by the torque meter and encoder provide feedback over the actual driveline's torque and speed. The magnetic powder brake (FAT 650) located on the test rig's end is controlled by the computer and it is coupled with a planetary gearbox (PLE080 by NEUGART GmbH). The test rig's software is developed in LabVIEW and National Instruments modules are exploited transfer control and acquisition signals between the computer and the experimental setup.

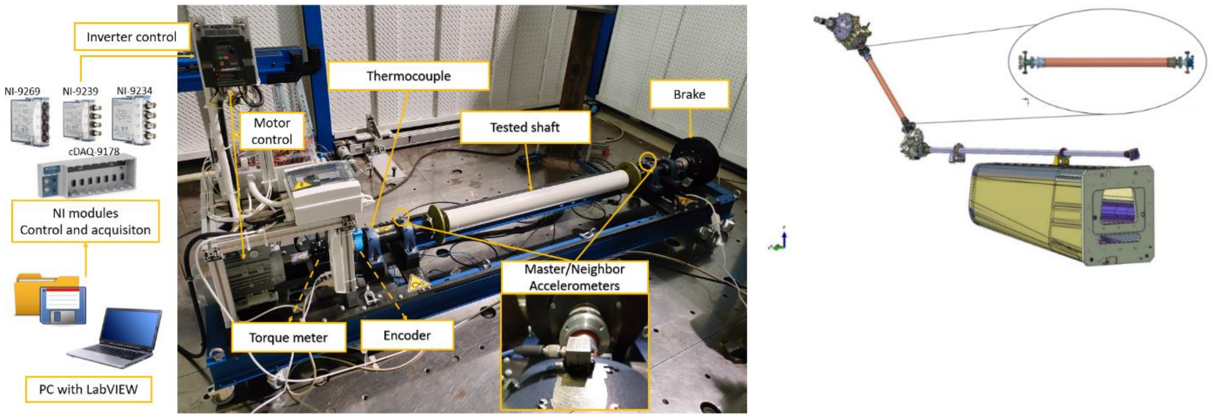

Figure 12. Left: The experimental setup. Right: Example of the Tail Rotor Drive System (TRDS) of a helicopter, with the slant shaft subjected to ballistic impact.

Despite the controlled input, some uncontrolled stochastic effects and variations in bearing temperatures, influenced by environmental conditions during use, alter the system response. These variations generate the risk of inducing false damage detection in the developed algorithms. The temperature is the principal operating condition prone to variations, altering the physical properties of the bearings' lubricant. To evaluate this parameter, a thermocouple is mounted on the nearest bearing to the motor. The test rig operates with the temperature of the bearings oscillating between $33°C$ and $43°C$. In order to capture the variations of the confounding influences, the test was performed five times, with each run performed under different bearings temperatures. The experimental data obtained from the Master and Neighbour accelerometer, as well as the different testing temperatures are shown in Figure 13.

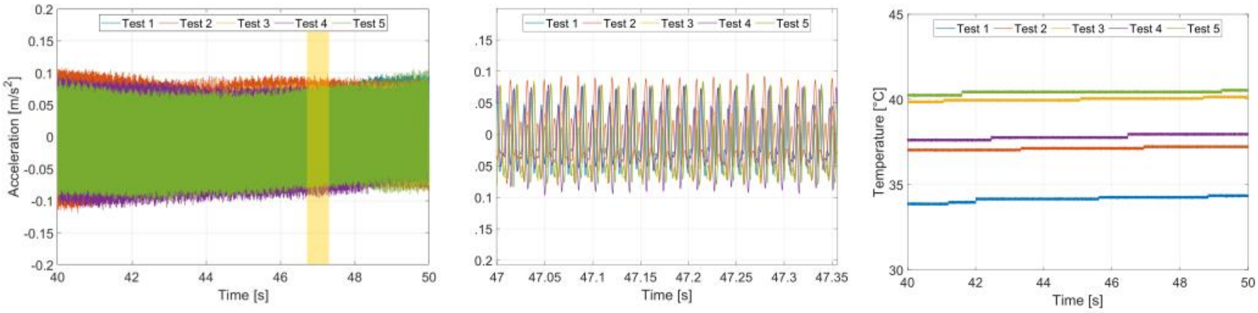

Figure 13. Acquisitions during dynamic tests on the rotating shaft and temperature readings from the thermocouple sensor.

Ballistic impact tests were conducted in a dedicated shooting range using General Dynamics 12.7x99 AP projectiles. Impact velocities ranged from 600 m/s to 900 m/s, resulting in increased severity (Figure 14). Projectile velocity was measured in pre-impact and post-impact zones using measurement barriers placed as close as possible to the test bench. The experimental design comprised two iterations, involving two distinct tail rotor slant shafts, each subjected to a single ballistic impact event. A high-speed camera recorded the shooting occurrence, while vibration signals at the supports were meticulously acquired through accelerometers.

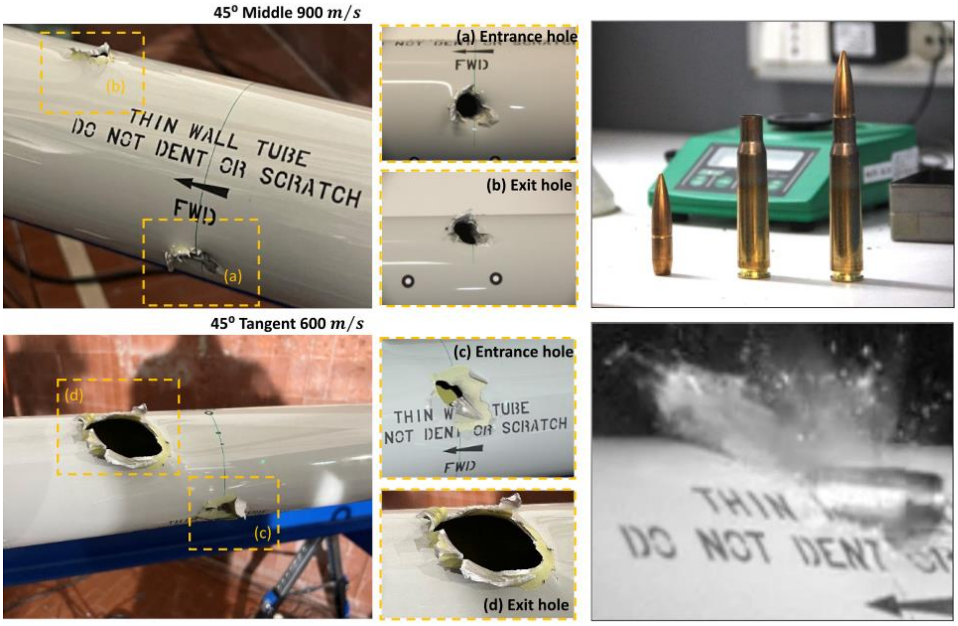

Figure 14. Left: Ballistic test for different impact performed on rotors 1 and 2. Right: The General Dynamics 12.7x99 AP projectile and footage from high-speed video of the tangential shoot.

3.2. PERFORMANCE

The estimation model was trained using the Adam optimizer with a batch size of 50 samples and 150 epochs. The hyperparameters were fine-tuned for optimal training solutions after dedicated optimization analysis. The training was conducted on a system with an Intel Core i7-8700 CPU, an NVIDIA GeForce GTX 1060 6GB GPU, and 48GB of RAM. The dataset of 5000 samples was randomly split into 80% training and 20% test sets. The NARX model was validated on acquisitions from baseline, as illustrated in Figure 15, achieving a maximum Mean Squared Error (MSE) of $3 \cdot 10^{-4}$. The error distribution for each input signal demonstrated the stability of the model against operational uncertainties like ambient conditions and loading. These uncertainties were inherently captured in the training process and reflected in the model's accuracy.

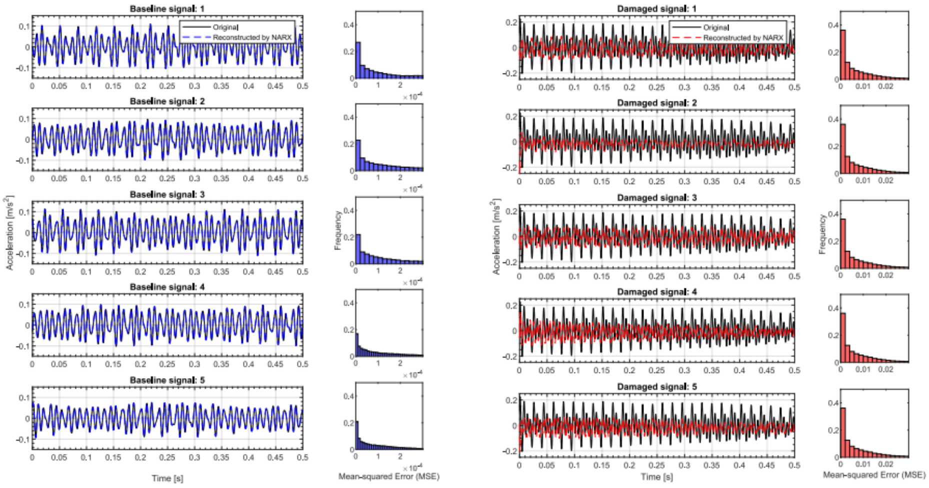

Figure 15. The NARX model estimates time series at the baseline and damaged state, respectively.

As soon as the ballistic test with impact velocity 900 m/s and inclination $45°$ is performed at the middle of the rotor, an alteration at the vibration response of the system is observed, while the performance of model in estimating unseen time series is expected to significantly decrease. Greater magnitude of vibrations is expected for the second rotor which is subjected to ballistic impact with velocity 600 m/s and inclination $45°$ performed tangentially. The database used to test the performance of the estimation model in damage detection is referred as PI R(1-2) - BS, corresponding to acquisitions made at the post-impact phase at the nominal speed for both ballistic impact tests. In Figure 15, the reconstructed time series is compared with the actual input signal, revealing a sharp decrease in the model performance. As a matter of fact, the estimation error distributions at the baseline and damaged dataset are illustrated in Figure 16. These distributions are normalized to the range [0,1] for damage detection comparison, mitigating the effect of filtering. Notably, the NARX model exhibits great discrepancy between the two states, indicating good performance in ballistic damage detection.

Additionally, it was observed that the center of gravity (CoG) of the error distribution follows a trend consistent to the increase in the system response due to the presence of damage. Figure 16 illustrates the monitoring of the x-coordinate of the CoG for the estimation model. Upon introducing impact damage, the CoG sharply increases, showing a significant deviation from the baseline. In fact, a noticeable distinction between the two states emerges, with a notable increase in the dispersion of data points primarily attributed to the occurrence of ballistic damages, effectively isolating its effect amidst confounding influences. Nevertheless, in the event of a helicopter operating and sustaining impact damage, prompt and reliable notification to the crew is essential. This is accomplished by setting up a robust threshold, above which an alarm is triggered. Various methods have been suggested for establishing the damage detectability threshold, with this study focusing on the outlier analysis proposed by **Error! Reference source not found.**. Outlier analysis is a statistical technique employed to identify observations that significantly deviate from the majority of vibration data, categorizing them as outliers.

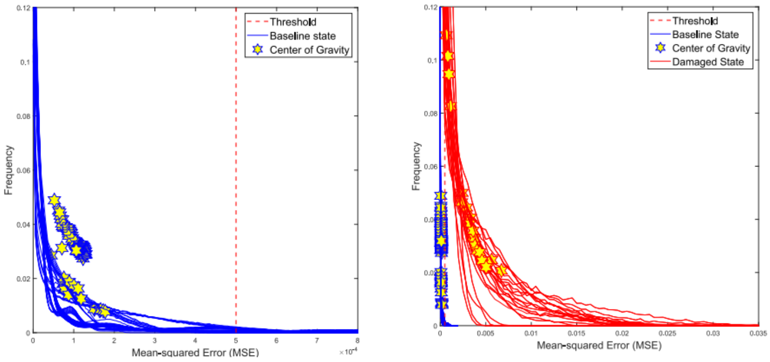

Figure 16. Error distribution of the NARX model for the baseline and the damaged state.

In general, the threshold is a crucial parameter for the sensitivity and reliability of the damage detection system and thus careful adjustments are required to avoid misclassifications and missing damage detection. Specifically, misclassification is described by the probability of a false alarm, while the detection is described by the probability of damage. The goal is to achieve a balance between false positives or negatives alarms and damage detection. In the event of a false alarm, the consequences are associated with unnecessary economic and time costs stemming from maintenance activities, as well as potential mission delays and related penalties. On the other hand, the absence of damage detection results in severe repercussions, as it jeopardizes the condition of the helicopter, and the overall success of the mission. In this study, given the relatively controlled laboratorial environmental, the definition of the threshold was performed based on a simplistic approach, while a good damage detection performance was achieved as illustrated in Figure 17.

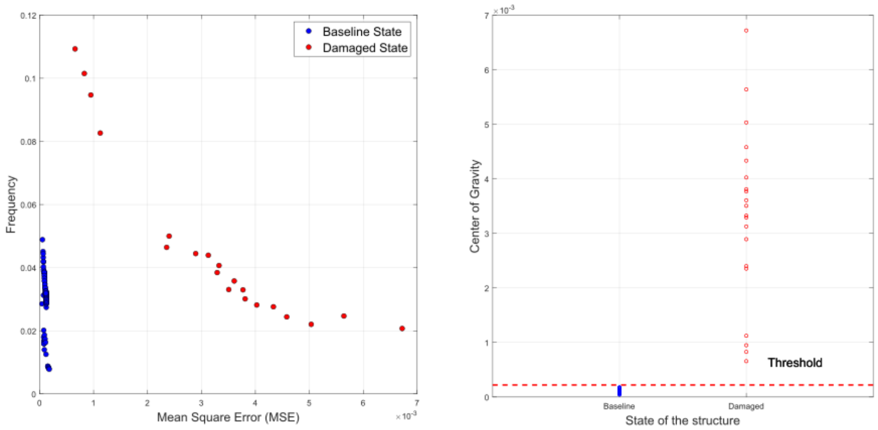

Figure 17. The CoG of each error distribution the two states. Outlier analysis establishes a threshold above which an alarm is triggered.

On the battlefield, the detection of damage is usually insufficient, as the location and extend of the damage are proven to be crucial for effective monitoring. This study aims to utilize the NARX estimation model for damage identification. Focusing on the post-impact phase, it is noteworthy that the CoG demonstrates an increase between the PI R1-BS and PI R2-BS states, corresponding to runs at the nominal rotating speed for the two rotors, respectively. Figure 18 indicates that the estimation error is significantly influenced by the damage severity in terms of dimension and position. Not only does the CoG value elevate with increasing impact severity, but the dispersion of the data points also intensifies. However, the model does not exhibit a comparable sensitivity to damage severity when processing signals acquired at the PI R1-TS and PI R2-TS states, where resisting torque is applied. A plausible explanation for this phenomenon could be attributed to the resisting torque generated by the brake, which counteracts the effect of increased damage severity, resulting in an attenuation of vibrations as the rotor is compelled to decelerate. Acknowledging the promising potential of the NARX model, it is recognized that the framework serves as an initial step toward developing a tool for online damage identification incorporated into military helicopters.

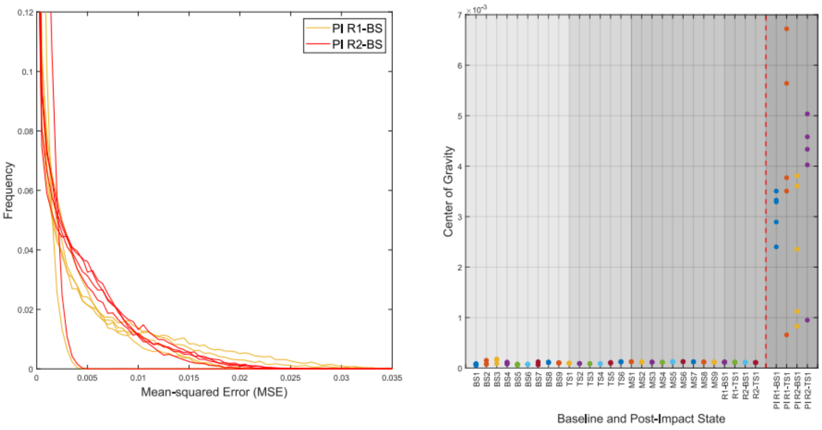

Figure 18. The error distribution demonstrates sensitivity to the severity of the impact. CoG remains a robust feature for ballistic impact damage detection based on the NARX model.

4. CONCLUSIONS

In the context of defence technologies, advancements in airborne early warning systems through the incorporation of Machine Learning methods contribute to enhancing EU military capabilities in terms of cost, time, and the overall success of missions. In this study, NARX Recurrent Neural Network designed for detecting the occurrence of ballistic impact damage on a helicopter tail rotor slant shaft have been developed. The approach leverages variations in vibration signals obtained before and after a ballistic impact to assess the structural integrity of the shaft.

This is achieved by employing a damage-sensitive feature derived from the model estimation error distribution, which proved to be capable of distinguishing damaged and normal conditions, though additional effort will be dedicated in future activities for obtaining useful indication for damage assessment. This might involve the testing of different signal features incorporating the effect of confounding influences both in the normal and damaged conditions, allowing for more robust indications and a clearer trend of damage indicators as a function of the damage extent. These thorough investigations are essential to rigorously test and challenge the performance of the proposed estimation model.

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References

[1] Peter B.M.J. Pijpers, Mark Voskuijl, Robert J.M. Beeres, (2023) “Towards a data-driven military”, Leiden University Press, Faculty of Military Sciences, Netherlands Defence Academy.
[2] Hamed Alqahtani, Gulshan Kumar, (2024) “Machine learning for enhancing transportation security: A comprehensive analysis of electric and flying vehicle systems”, Engineering Applications of Artificial Intelligence, Vol. 129, 107667.
[3] Alessandro Marrone, Michele Nones, (2015) “The Role of Dual-Use Helicopters in the Security and Defence Field”, Istituto Affari Internazionali (IAI), pp 137-160.
[4] Chao Zhang, Rupeng Zhu, Dan Wang, Peng Cao, (2021) “Dynamic characteristics analysis and the identification signal of the horizontal tail drive shaft system with the ballistic impact damage of a helicopter”, Defence Technology, Vol. 17, pp 416-428.
[5] [Jordi Cusido, Luis Romeral, Juan Antonio Ortega, Javier Rosero Garcia, (2008) “Fault detection in induction machines using power spectral density in wavelet decomposition”, Transactions on Industrial Electronics, Vol. 55, pp 633–643.
[6] Yaowen Ou, Eleni Chatzi, Vasilis Dertimanis, Minas D Spiridonakos, (2016) “Vibration-based experimental damage detection of a small-scale wind turbine blades”, Structural Health Monitoring, Vol. 28, No. 6.
[7] Yanxin Xu, Dongjian Zheng, Chenfei Shao, Sen Zheng, Hao Gu, Huixiang Chen, (2023) “Real-time diagnosis of structural damage based on narx neural network with dynamic response”, Mathematics, Vol. 11, pp 1281.
[8] Keith Worden, Manson Graeme, Nicholas R.J. Fieller, (2000) “Damage detection using outlier analysis”, Journal of Sound and Vibration, Vol. 229, pp 647–667.

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A NEW COVERT ERA IN MARITIME SURVEILLANCE AND RECONNAISSANCE

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Abstract

While passive radar exploiting terrestrial illuminators is now a mature technology with several commercial systems available on the market, the exploitation of satellite illuminators is still an open field of research. Nonetheless, satellites might offer signal coverage and therefore might enable passive radar operation in remote areas like at open sea. This is very relevant for platforms specifically designed to be stealth or to operate as silently as possible, like for instance submarines. In this work, we propose to exploit satellite illuminators for passive radar imaging in a maritime scenario. In particular, the system architecture of an existing experimental system developed at Fraunhofer FHR is described. Results of its corresponding experimental validation show the proof of principle of this technology. Finally, an analysis is conducted over the possible integration of this system in a more complex System-of-Systems architecture.

Keywords

Passive radar, radar imaging, covert surveillance.

1. INTRODUCTION

Passive radar can offer all the known features of radar surveillance (such as day and night visibility, independent of weather conditions) with the additional strategic advantage to operate covertly. Passive radar has now reached technological maturity with various systems commercially available worldwide [1][2][3][4][5]. All commercially available passive radar systems rely on broadcast terrestrial transmitting infrastructures such as FM-radio, digital radio (DAB), and digital television (DVB-T(2)).

However, over the last few decades we have experienced a surge of importance of the space sector, and of commercial communication and broadcast services provided from space. This has drawn the attention of the passive radar community, aiming at investigating the capabilities of such signals as illuminators of opportunity, [6][7][8][9][10][11][12][13]. While no commercial passive radar based on space illumination exists, this paper is devoted to presenting a potential operational context for satellite based passive radar. It is clear that satellite signals constitute a valid source of illumination where no terrestrial infrastructure is available, and this is especially true in remote areas and at open sea. Satellite signals might be available in remote areas because their services are specifically intended to be offered all over the Earth surface (as it is the case for global navigation satellite systems, GNSS), or simply because the satellite antenna footprints are so wide that also coastal and remote areas are covered (as in the case of geostationary broadcast illuminations). Regardless of the above reasons, exploitation of satellite signals for passive radar purposes might offer several strategic advantages in military scenarios: (i) a space-based transmitting infrastructure is generally more difficult to be torn down by the enemy in a battlefield situation; (ii) satellite illuminating infrastructure, although exploited in a non-cooperative way, might be operated by friendly nations also over enemy territory;

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(iii) a space-based passive radar designed to exploit a satellite signal available worldwide would be able to operate worldwide with perhaps only minor modifications. This is of critical importance in order to reduce development and mission planning costs; (iv) maritime open sea military scenarios are characterized by stealth platforms, like for instance the USS Zumwalt Destroyer [14] or submarines (e.g. the U212, [15]) for which the capability to operate silently is of highest importance, [16].

In this paper, we present some proof of concept for satellite-based surveillance at open sea by means of passive radar imaging. The remainder of this paper is structured as follows. In Section 2, the scenario is presented together with an overview of possible space illuminators for passive radar. Section 3 presents and proposes a system architecture, which stems from experimental systems developed over the last few years at Fraunhofer FHR, Germany. In addition, an experimental validation is reported showing a proof of concept for the proposed approach. Section 4 is devoted to considerations on how such satellite based passive radar can be integrated in a more complex system-of-systems, and which benefits might derive from the integration. Finally, in Section 5 we briefly summarise the main advantages and the military impact and draw our conclusions.

2. POTENTIALS AND CHALLENGES OF PASSIVE RADAR IMAGING EXPLOITING SATELLITE ILLUMINATORS

The exemplary operational scenario under consideration is sketched in Figure 19. A military platform (in this case a submarine) is operating at open sea and it requires reconnaissance of another maritime target, whose presence might have been detected by other means (see Section 4 later on).

Figure 19: Considered scenario

The proposed idea is to exploit passive radar technology from the submarine to retrieve (in a completely silent mode) additional information about the target. This can be done for instance in terms of passive radar imaging via inverse synthetic aperture radar (ISAR) approaches. ISAR can provide extremely relevant information about a non-cooperative target by exploiting the relative rotational motion between the radar and the target. By doing so, and depending on the available spatial resolution, target length and width can be estimated as well as information about the shape of the target itself (e.g. the presence and shape of super-structure). This information is proven to help subsequent target classification and recognition stages, [17]. A submarine is here considered as a typical military platform constrained to operate as silent as possible, and for which the exploitation of passive radar technology might be of particular interest. However, when operating a passive radar at open seas, terrestrial illuminating infrastructure is typically absent or so far away to be unusable. To this end, it becomes particularly attracting the possibility to exploit space-based illuminating infrastructure instead.

Nowadays, there are in fact several satellites providing radio frequency (RF) coverage ubiquitously over the Earth surface. A summary of possible satellite illuminators is reported in the following Table 3.

Among potential illuminators, GNSS constellations (like GPS, GLONASS, Galileo or Beidou) offer the interesting characteristic of persistent and continuous RF illumination over the whole Earth surface, and hence at open sea, although they show very limited signal density power levels measured at Earth surface. Consequently, a passive radar system relying on GNSS illumination might be severely limited in terms of maximum detection range making it of limited interest in operational military scenarios. Also, the signal bandwidth offered by GNSS illumination is fairly limited for radar imaging purposes (that is, 10 MHz of signal bandwidth provides a maximum theoretical range resolution of about 15 meters) [13].

Table 3: Overview of potential space illuminators for passive radar

	Orbit	Signal bandwidth	Signal power density at Earth surface [dBW/m^2]	Continuous illumination	Detection range
GNSS (GPS, Galileo, Beidou, Glonass)	MEO	up to 15 MHz in L-Band	ca. -130	yes	limited
DVB-S / **DirectTV** (e.g. Astra)	GEO	up to 2 GHz in Ku-Band	ca. -108	yes	medium/limited
FSS (Starlink, OneWeb)	LEO	up to 250 MHz in Ku-Band	ca. -98	yes	medium
SAR Constellations (e.g. Capella, Iceye)	LEO	over 1 GHz in X-Band	ca. -50	no	big

Commercial satellite constellations carrying SAR payloads have been recently deployed in low Earth orbit (LEO) like for example Capella Space [18], Iceye [19], and Umbra Space [20]. These constellations might offer, in contrast to GNSS, very strong signal power densities and very large signal bandwidths, as they are explicitly designed for radar imaging purposes. However, SAR constellations typically lack in proving a persistent RF-coverage. In fact, space-borne SAR transmit only over few minutes during their orbits around the Earth. The lack of signal reliability makes these signals of limited interest for passive radar purposes.

Fixed Satellite Services (FSS) constellations like Starlink [21] and OneWeb [22] potentially provide persistent RF-coverage over the entire Earth surface thanks to the huge number of satellites in their constellations. Signal power densities and signal bandwidths are also theoretically very well suited for passive radar imaging purposes. Specifically, current experimental validations [23] show signal bandwidths in the order of up to 240 MHz for both the Starlink and the OneWeb constellations. These systems are still under deployment and their exploitation as spaceborne illuminators for passive radar is currently an open research topic, [23]. In addition, as these systems are designed for communication purposes, the actual availability of downlink signals in remote areas might be limited [24] (or might require to be triggered by the passive radar itself, see also comments in Section 4 later on).

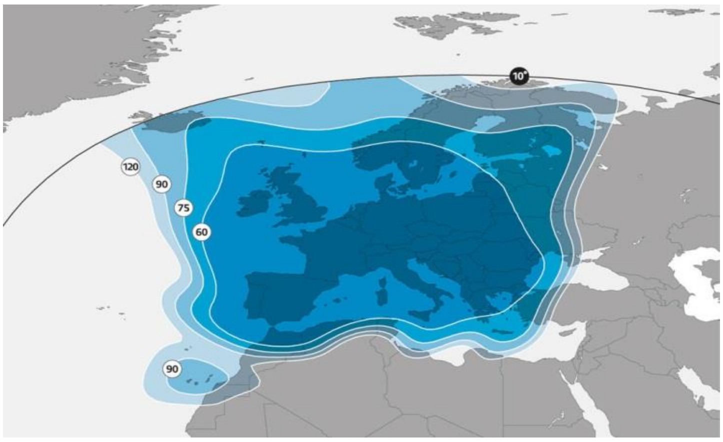


Figure 20: Illumination footprint of the ASTRA 19.2E satellite over Europe, from [24]. The different shades of blue indicate the required size of the dish antenna (in cm) for adequate signal reception.

Digital television broadcast services (such as DVB-S [25] in Europe) are typically broadcasted from geostationary satellites. Although those beams are indeed directed towards populated areas, the resulting footprints on the Earth surface are very large due to the very long distance and hence offer cover of coastal and open sea regions, as exemplary depicted for the ASTRA 19.2E illumination footprint shown in Figure 20. Being broadcasted signals, their bandwidth and persistence over time is intrinsically guaranteed and the signal bandwidth is large enough for radar imaging purposes. Specifically, the broadcast spectrum allocated to DVB-S ranges from 10.7 GHz to 12.75 GHz, and it is densely populated with several transponders, each having a bandwidth of about 30 MHz. As an example, part of the digitized DVB-S spectrum broadcasted by the ASTRA 19.2E satellite is reported in Figure 21 for both horizontal and vertical polarizations. As is apparent, there is a multitude of transponders adjacent to each other, which allows to increase the received signal bandwidth beyond that of a single transponder.

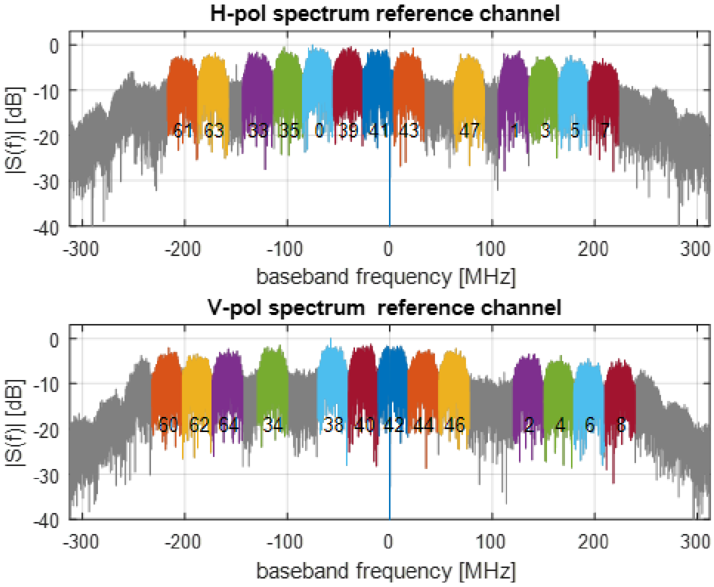


Figure 21: Part of the DVB-S digitized spectrum from ASTRA 19.2E in both H- and V- polarisations centred around 11.259 GHz. The different transponders are colour coded.

3. SYSTEM ARCHITECTURE AND EXPERIMENTAL VALIDATION

Fraunhofer FHR has been conducting experimental research activities on satellite based passive radar since few years now, [8], starting within the EDA Cat. B project 'Multichannel Passive ISAR Imaging for Military Applications (MAPIS) and continuing the activities later on. Over the years, several experimental setups have been developed under the SABBIA® program. Currently the SABBIA® system is constituted of two main sub-systems: a RF-front end and an antenna unit. The RF-front end is made from commercial off the shelf (COTS) components and it is responsible for down converting the signal from intermediate frequency (IF, after the LNB, see antenna sub-system later on) to base band and to digital sampling. It comprises 8 parallel receiving channels that are able to operate fully phase coherently. Each receiving channel is connected to an analog-to-digital converter sampling the signal at 625 MSamples/s with 8 bits/sample. Alternatively, if operating with only 4 receiving channels, the sampling rate can be doubled to 1250 MSamples/s. Data are then stored internally for subsequent off-line processing.

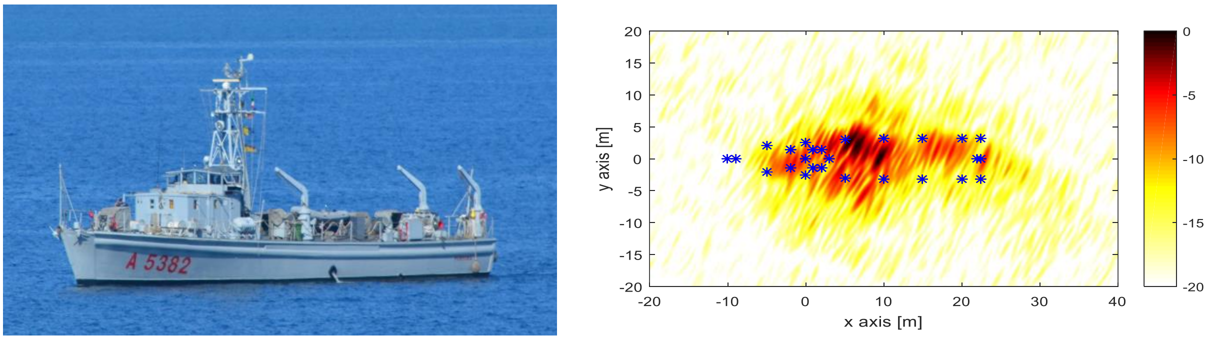
The SABBIA® antenna sub-system is highly configurable. There are basically two antenna options that can be utilized. The first is a set of two mechanically steerable dish antennas. The dish antennas have a diameter of about 90 cm, providing a pencil beam of 2° width with circa 40 dB of gain. They have a four-axis motor (yaw, pitch, roll, skew) and a rotation speed of about 50°/second. These motors, together with an embedded internal measurement unit (IMU) can compensate the platform motion and to keep the antenna steered towards a specific direction. One of the two dish antenna, namely the one connected with the surveillance channel, is equipped with a high-resolution camera, which is used to verify correct steering during experimental validations. Each dish antenna is also equipped with two COTS Quad-LNBs, one for H- and one for V-polarisation reception. The LNBs are GPS-disciplined and they all receive a single 10 MHz reference tone, which is crucial to guarantee phase coherence among all receiving channels. LNBs perform a low noise amplification of the signal to guarantee low noise figure in the receiver and they also perform a first down conversion of the signal from RF to an IF at about 2 GHz.

The second antenna option is constituted by a set of two electronically steerable antennas. These antennas are COTS, they are about 1 meter wide and offer similar beamwidth and gain as the mechanically steerable ones. They also have a low profile and are therefore particularly suited for integration within a moving platform. As in the previous case, the antenna units are equipped with an embedded IMU that can be used to maintain antenna steering in specific directions. Clearly, this is done in real-time via software. Differently from the mechanically steerable antennas, in this case only one single polarization can be digitized at each time, as the low-profile case of each antenna can only host one single Quad-LNB. Also, some internal embedded filtering limits the maximum bandwidth of the electronically steerable antennas to 250 MHz. It is worth noticing, that due to the flexible design of the SABBIA® system, it is possible to interchange and combine the two types of antennas depending on the specific needs. As an example, Figure 22 reports a possible setup with one mechanically steerable antenna for surveillance and one electronically steerable antenna for reference. Such configuration might be extremely interesting in scenarios where there is the need for rapid switching from one satellite to another, as might be the case for LEO illuminators. Similarly, multiple antennas for reception in the surveillance channels can be used, the only limit being the overall number of receiving channels not exceeding 8.

Figure 22: Potential setup for the SABBIA® system. In this case, one electronically steerable antenna is used for reference signal acquisition, and one mechanically steerable antenna is connected to the receiving channel. The RF-front end is hosted in the case in the center.

The SABBIA® system has been deployed in several configurations and field trials in order to provide an experimental validation of the satellite-based passive radar imaging. In the following, we report the main outcomes of two different measurements campaign that have been carried out in the last years.

The first measurement was conducted within the MAPIS project at the Italian Naval Academy in Livorno, Italy, [27]. A previous version of the SABBIA® system was operated from the coast, and a cooperative military ship (see Figure 23(a)) equipped with both GPS and IMU was cruising during the experiment at about one kilometer distance from the receiver. Being the target fully cooperative, target trajectory and attitude was measured and provided to the off-line passive ISAR processing. In this case, 80 MHz of DVB-S signal from the ASTRA 19.2E satellite were digitized and processed. ISAR processing was performed coherently integrating time intervals of about 1 second each, and then multi-looking six of them to improve the image contrast.



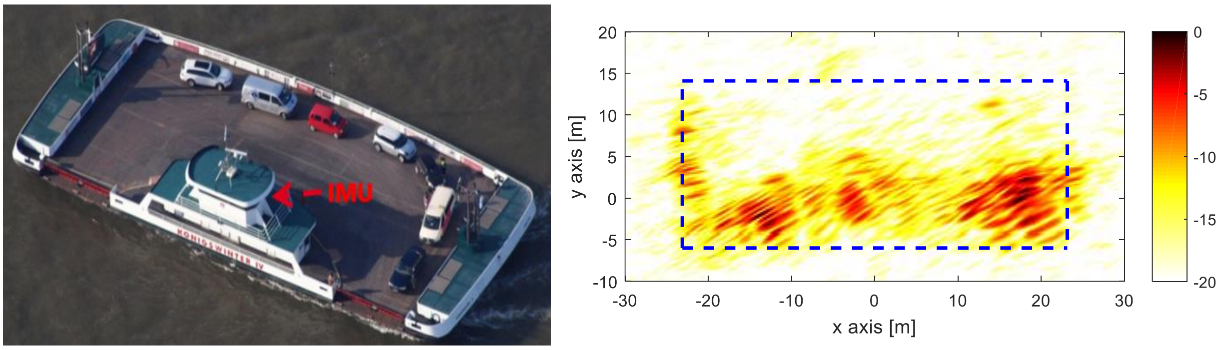
(a)

(b)

Figure 23: (a) Cooperative military ship (Porpora) used during the experiment in Livorno, Italy; (b) Passive radar image obtained via backprojection in top-view under assumption of known target motion, in [dB], from [27]. Blue markers sketch the shape of the target.

ISAR focusing was performed via backprojection, under the assumption of perfect knowledge of the target motion and attitude. A resulting image of the target is reported in Figure 23(b). As is apparent, the ISAR image can provide significant amount of information about the target, especially quite accurate estimation of the target length and width (see overlaid blue markers, sketching the actual ship's hull).

A second experiment was conducted along the Rhine river, this time exploiting a ferry (see Figure 24(a)) as a cooperative target, [28]. The SABBIA® system was deployed in a similar configuration as in the previous trial (that is, again digitizing 80 MHz of the DVB-S signal from the ASTRA 19.2E satellite), but now exploiting all polarimetric channels. ISAR processing was obtained via backprojection under assumption of perfect knowledge of target motion and attitude for each polarimetric channel separately. The different polarimetric passive ISAR images were then combined to increase information content of the ISAR product. The resulting ISAR image is reported in Figure 24(b). Again, non-coherent averaging over multiple ISAR images is performed to reduce noise background. As is apparent, the ISAR image mainly shows target return from negative values along the y-axis. This is due to shadowing effects of the rear part of the target due to low observing grazing angle. Results of this second experiment confirm both the feasibility of satellite-based passive ISAR and also demonstrate how this technique can be conveniently used to retrieve significant information about target shape.



(a) (b)

Figure 24: (a) Aerial image of the ferry used as cooperative target during the experiment along the Rhine river, Germany; (b) Passive radar image obtained via backprojection in top-view under assumption of known target motion, in [dB], from [28]. Blue dashed line sketches the shape of the target.

A final comment is in order. Both shown results assume a perfect knowledge of the target motion. This is clearly a non-realistic assumption in military operational scenarios. To this end, some work has been done on removing this hypothesis, [29]. The assumption of perfect target motion allows us to set an upper bound of the performance that satellite-based passive ISAR might achieve, neglecting at first the problem of target motion estimation, which has been already widely addressed in ISAR literature, [30].

4. INTEGRATION IN A SYSTEM-OF-SYSTEMS

Satellite-based passive radars typically exploit high gain pencil beam antennas to compensate for a relatively low signal power density at Earth surface. Pencil beam antennas are not particularly suitable for search new targets in a 3D-space. Especially when each antenna search position requires a fairly long integration time to cope with weak target signal echo. To this end, it might be interesting to integrate the satellite-based passive radar within a System-of-Systems and let other sensors detect the presence of a target, while retain the target imaging task for the passive radar. A viable solution might be to exploit a passive emitter tracker (PET) for target detection and localization ([31]), since PET also operate passively. That means, the RF emissions from the target itself would be exploited to detect and localize the presence of a target. The information is then passed to the satellite-based passive radar that can perform passive radar imaging of the target, in order to acquire additional information that can be then exploited for target classification and recognition. An exemplary block diagram for this architecture is sketched in Figure 25.

An additional interesting features resides in the possibility to use the satellite-based passive radar receiver with both broadcasted digital television signals (such as DVB-S(2)) and FSS (such as Starlink or OneWeb). This is in principle possible since the two illuminators share the very same frequency band, namely from 10.7 GHz up to 12.75 GHz. Since FSS satellites operate in LEO and are therefore moving, imaging capabilities would extend from ISAR to SAR also. This option would not only increase the robustness and resilience of the passive radar system, but it would also in principle enable an interconnection between the passive radar and a communication unit. In fact, as FSS signals might not always be actively transmitting, the receiver might trigger the FSS satellite to transmit and therefore to illuminate the area of interest. At the same time, the established communication link to the FSS satellite can be used to integrate the carrying platform in a multi-platform setup. It is worth noticing, that when exploiting the uplink communication from the platform to the FSS satellite, the platform itself would not be silent anymore, so this should be duly considered in an actual operational scenario. Nonetheless, said setup would enable an elegant integration and interoperation between sensing and communication, which is also in line with the System-of-Systems paradigm.

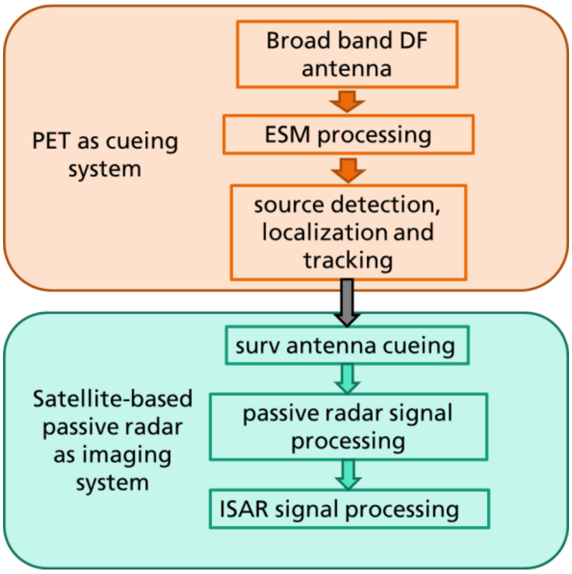


Figure 25: Block diagram of a potential integration between PET and satellite-based passive radar in a System-of-Systems.

5. BENEFITS AND MILITARY IMPACT

The proposed satellite-based passive radar imaging might significantly influence the operational maritime battlefield in the next decades. Adding target imaging capability in a pure silent mode can bring significant strategic advantage and thus guaranteeing domain superiority. The covert nature of the proposed system nicely fits with the stealth features of many platforms operating in maritime scenarios, being sub-marines the clearest example. As mentioned above, passive radar (although based on terrestrial sources of illumination) is already a mature technology with several commercial systems on the market. This demonstrates the interest and the general appreciation of its strategical advantages. The exploitation of satellite illuminators is the next consequent development in this area that the industries are likely to pursue in the upcoming years.

Results reported in this work show low to medium TRL for satellite-based passive radar imaging. They also show that existing computational capability and hardware miniaturization do not pose significant hurdles in developing this technology to higher TRLs. Section 4 also speculates on how such a system can be inter-connected in a more complex eco-system of sensing and communication. This is relevant not only because it is in line with current trends of multi-platforms and System-of-Systems architectures, but also because such integration is expected to increase robustness against failures, resilience, and therefore, more in general, to reduce development and deployment costs.

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References

[1] TwinVis Passive Radar, Hensoldt, https://www.hensoldt.net/stories/twinvis-passive-radar, accessed 08.03.2024.

[2] Maverick M-Series, Silentium Defence, https://www.silentiumdefence.com.au/our-solutions/maverick-m-series/, accessed 08.03.2024.

[3] Stealth, Daronmont, https://daronmont.com.au/products/passive-radar, accessed 08.03.2024.

[4] Pointer, Pro-Patria, https://propatria-inc.com/products/radars/pointer-en, accessed 08.03.2024.

[5] Aulos, Leonardo, https://electronics.leonardo.com/en/products/aulos, accessed 08.03.2024.

[6] D. Cristallini et al., “Space-based passive radar enabled by the new generation of geostationary broadcast satellites,” 2010 IEEE Aerospace Conference, 2010, pp. 1-11.

[7] D. Pastina, M. Sedehi and D. Cristallini, “Passive bistatic ISAR based on geostationary satellites for coastal surveillance,” 2010 IEEE Radar Conference, 2010, pp. 865-870.

[8] S. Brisken, M. Moscadelli, V. Seidel and C. Schwark, “Passive radar imaging using DVB-S2,” 2017 IEEE Radar Conference (RadarConf), 2017, pp. 0552-0556.

[9] I. Pisciottano, D. Cristallini, D. Pastina, “Maritime target imaging via simultaneous DVB-T and DVB-S passive ISAR,” IET Radar, Sonar & Navigation, Volume 13 (2019), Issue 9, p. 1479 –1487.

[10] R. Blázquez-García, M. Ummenhofer, D. Cristallini and D. O'Hagan, “Passive Radar Architecture based on Broadband LEO Communication Satellite Constellations,” *2022 IEEE Radar Conference (RadarConf22)*, New York City, NY, USA, 2022, pp. 1-6.

[11] H. Ma, et al., “Maritime moving target indication using passive GNSS-based bistatic radar,” IEEE Transactions on Aerospace and Electronic Systems, vol. 54, no. 1, pp. 115-130, Feb. 2018.

[12] F. Santi, F. Pieralice, D. Pastina, "Joint Detection and Localization of Vessels at Sea With a GNSS-Based Multistatic Radar," IEEE Transactions on Geoscience and Remote Sensing, vol. 57, no. 8, pp. 5894-5913, 2019.

[13] D. Pastina, F. Santi, F. Pieralice, M. Antoniou, M. Cherniakov, “Passive radar imaging of ship targets with GNSS signals of opportunity,” IEEE Transactions on Geoscience and Remote Sensing, vol. 59, no. 3, pp. 2627-2624, Mar. 2021.

[14] *USS Zumwalt* (*DDG 1000*), https://www.navy.mil/Resources/Fact-Files/Display-FactFiles/Article/2391800/destroyers-ddg-1000/, accessed 08.03.2024.

[15] U212 Near Future Submarine, https://www.occar.int/our-work/programmes/u212-nfs, accessed 08.03.2024.

[16] New frontiers in passive radar and sonar, Military + Aerospace Electronics, https://www.militaryaerospace.com/communications/article/16709052/new-frontiers-in-passive-radar-and-sonar, accessed 08.03.2024.

[17] A. Manno-Kovacs, et al., "Image based robust target classification for passive ISAR," IEEE Sensors Journal, vol. 19, no.1, 2018, pp. 268-276,

[18] Capella Space, https://www.capellaspace.com/, accessed 08.03.2024.

[19] Iceye, https://www.iceye.com/, accessed 08.03.2024.

[20] Umbra Space, https://umbra.space/, accessed 08.03.2024.

[21] Space Exploration Holdings, LLC, “Application for modification of authorization for the SpaceX NGSO satellite system,” FCC filing SAT-MOD-20200417-00037, 2020.

[22] WorldVu Satellites Limited, “OneWeb non-geostationary satellite system,” FCC filing SAT-LOI-20160428-00041, 2016.

[23] R. Blázquez-García, et al., “Capabilities and challenges of passive radar systems based on broadband low-Earth orbit communication satellites,” IET Radar Sonar Navigation. 18 (1), 78–92 (2024).

[24] D. Cristallini, R. Blázquez-García, D. O'Hagan, „K-Space Signal Occupancy of Starlink Signals and their Applications in Passive Radar Imaging”, 2023 IEEE Radar Conference (RadarConf23), pp.1-6.

[25] Digital Video Broadcasting (DVB); Second generation framing structure, channel coding and modulation, systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications (DVBS2), ETSI EN 302 307-1, November 2014, v 1.4.1.

[26] ASTRA 1KR, SES, https://www.ses.com/our-coverage/satellites/335, accessed 08.03.2024.

[27] I. Pisciottano, D. Cristallini, D. Pastina, “Maritime target imaging via simultaneous DVB-T and DVB-S passive ISAR, ” IET Radar Sonar Navigation, 13: 1479-1487.

[28] I. Pisciottano, F. Santi, D. Pastina and D. Cristallini, "DVB-S Based Passive Polarimetric ISAR - Methods and Experimental Validation," in IEEE Sensors Journal, vol. 21, no. 5, pp. 6056-6070, 2021.

[29] F. Santi, I. Pisciottano, D. Cristallini and D. Pastina, "Impact of Rotational Motion Estimation Errors on Passive Bistatic ISAR Imaging via Backprojection Algorithm," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 17, pp. 3345-3365, 2024.

[30] V. C. Chen, M. Martorella, Inverse Synthetic Aperture Radar Imaging: Principles, Algorithms and Applications. The Institution of Engineering and Technology, 2014.

[31] D. Cristallini, I. Pisciottano and H. Kuschel, “Multi-Band Passive Radar Imaging Using Satellite Illumination,” 2018 International Conference on Radar (RADAR), Brisbane, QLD, Australia, 2018, pp. 1-6.

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CROWS: COMMON RESILIENT OPERATIONAL WEATHER SYSTEM

D. Sládek[1]

Abstract

Rapid advancements in information technology and artificial intelligence (AI) are reshaping traditional disciplines such as meteorology, which has historically been crucial for military and humanitarian operations. Despite the advancements in meteorological data reliability and standardization, there remains a need for innovative approaches to leverage these developments effectively.

This paper proposes a hierarchical system that harnesses archival data from global and local models, along with observations, to address this need. Using machine learning (ML) techniques, the system performs quality control, partitions data by region of interest, and assigns aggregate metadata to products. It also predicts outlier phenomena critical to operations, facilitating the creation of defence-oriented and user-needs-based products.

In contrast to conventional numerical models, the proposed system integrates traditional meteorological concepts with AI. It not only checks and evaluates forecasts but also retrospectively diagnoses inputs and outputs, empowering both AI systems and human users. By providing simplified information on weather reliability, variability, and suitability for activities and operations, it enhances decision-making across various branches.

Keywords

Weather forecasting, AI forecasting, machine learning, decision-making support, data quality.

1. INTRODUCTION

Extensive meteorological databases are indispensable across various sectors including meteorology, aviation, humanitarian operations, maritime activities, and GNSS processing. While standardized by organizations like the WMO and ICAO, the diversity in processes, products, and pipelines across European countries poses significant challenges. This lack of uniformity hampers operational cohesion and decision-making capabilities.

The problem lies in the difficulty users encounter in interpreting complex meteorological data, understanding probabilities, and accessing tailored products promptly, thus impeding timely decision-making and efficient utilization of weather insights.

In the European context, the regulation 2023/138 [1] defined meteorological data as High-value Dataset (HVD) and directed it to be publicly available, being deployed by 9 June 2024. This will open the door to new possibilities for archiving and data processing.

In meteorology, extensive meteorology databases (such as [2]) are essential for weather forecasting, climate monitoring, and understanding atmospheric phenomena [3], support humanitarian operations and prepare to climate-related health risks [4]. Also, integration of meteorological information in humanitarian logistics helps in decision-making processes and resource allocation during crises [5]. For the maritime operations, these databases provide

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critical information on wind patterns, wave heights, and storm forecasts, aiding in navigation and operational decision-making [6]. Furthermore, meteorological databases are utilized to detect and forecast various hazards for aviation, including turbulence, icing, snow, cumulonimbus clouds, intense rainfall, and volcanic ash [7] .

Other application fields that may not be immediately apparent include GNSS processing, which derives benefits from meteorological databases through the development of atmospheric correction models and the provision of space weather data [8]. Additionally, meteorological databases serve as valuable resources for civil protection efforts, enabling wildfire analysis and management, among other applications [9] spanning a wide range of domains.

Commercial solutions are making strides in leveraging meteorological databases, with companies like Synoptic and Meteomatics [13],[14] from companies providing data to companies developing solutions for urban drone operations, such as TruWeather and Unisphere [15],[16] . While these commercial solutions typically offer high-quality services, they often lack the necessary data transparency and flexibility found in the research methods. These alternatives, which include functionalities like warning systems for hazardous phenomena, support for terrain clearance, aviation assistance, artillery guidance, satellite imagery analysis, fire prediction, and mitigation of humanitarian threats, provide valuable alternatives for users. Notably, specific databases often do not archive model runs, limiting the ability to analyse forecast data retrospectively and potentially hindering the development of more robust solutions.

Although there are pan-European initiatives like SESAR [12] or Copernicus [17], they are focused primarily on aviation, environmental sciences, etc. The CROWS proposal expands on general meteorological projects with several principles:

1. Relevance: Data presented to users directly concern them and their critical values.
2. Blending: Data do not originate from a single source, but mainly from archived and verified sources that can mutually validate each other.
3. 5 dimensions: Data and products are archived and modelled with connections among them in space, height, time, and among the products themselves.
4. Quick response: Data and products are pre-processed for a set of similar applications, so new products will be based on pre-processed foundations.

Given these challenges, this research seeks to improve risk-based mission planning through innovative, continuous and automated analysis of meteorological data and forecasts. To this end, we propose new methodologies focused on advanced preprocessing, data combining, multidimensional modelling, and rapid response strategies. The following sections describe our methodology and provide insights into how these approaches can be used in practice to improve decision-making in various weather-dependent sectors.

2. METHODOLOGY

The proposed system consists of three fundamental database processing layers (Figure 26), each accompanied by a set of machine learning methods specifically calibrated for working with the respective datasets. Initially, data collection is performed, followed by immediate statistical checks and comparison using machine learning methods to detect outliers, anomalies, extremes, or gaps. Subsequently, the data are processed into user-friendly products using statistical, machine learning, and visualization tools. The third step involves retrospective analysis to evaluate the accuracy of analytical and predictive methods. Based on the chain of steps, reduction algorithm is applied to drop the data that are not necessary to store. Each of these products can then be supplemented with a dataset of retrospective evaluations to determine its quality and reliability.

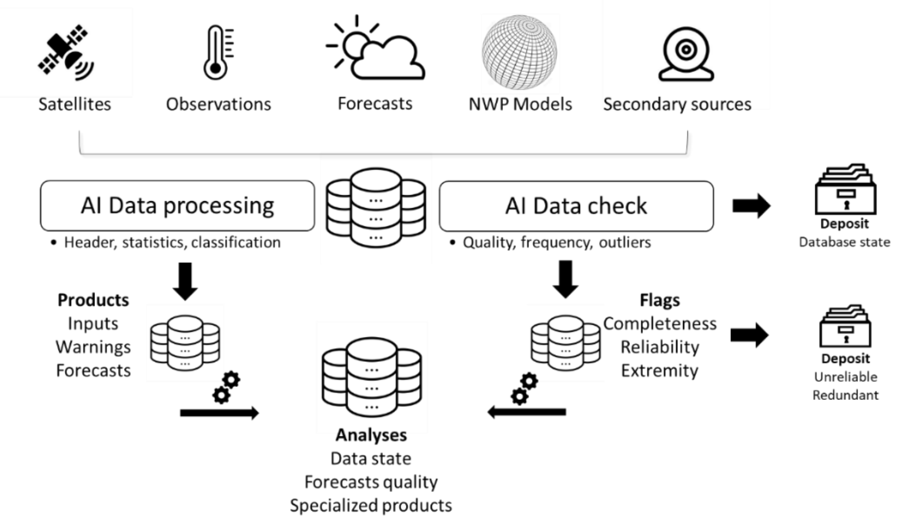


Figure 26. Overview of the data collection process and subsequent analysis steps.

The data collection process involves real-time evaluation of frequency, outliers, extremes, followed by classification into smaller datasets, labelling, and statistical summarization. Subsequently, analysis of products, data flags, success rate assessment, and production of final products occur.

The system illustrated in the Figure 26, begins with databases, which are currently organized at the national level in Europe, and also at the international level under the authority of the European Centre for Medium-Range Weather Forecasting (ECMWF) or the WMO. However, standardized processing, archiving, automated sorting, or the automated creation of defence-oriented products have not yet been implemented within these databases.

2.1. DATA SORTING

Presently, each state manages its own data resources, including various models and observations that often originate in different formats. While aviation data adheres to strict ICAO standards, achieving similar levels of standardization across other sectors poses challenges due to the complexities of international collaboration. The proposed model aims to streamline data collection across multiple tiers:

1. Global Level: Involves gathering data from sources like satellite observations and global-scale models.
2. International Level: Includes data from larger domain models, radar networks, and aircraft observations.
3. National Level: Encompasses local models, ground-based observations, national forecasts, and alert systems.
4. Secondary Level: Consists of additional sources such as webcams, localized forecasts, and informal measurements.

These data are sorted, processed, divided into the required smaller parts (e.g. by location), into suitable formats [10] and given a header (Figure 27). This header contains essential metadata including data type, quantities, altitude levels, reference time, as well as static indicators such as maximum and minimum values, standard deviations, and indicators for missing data. This approach enables efficient searching for specific phenomena, such as extreme events, directly through the header information without the need to unpack large data files.

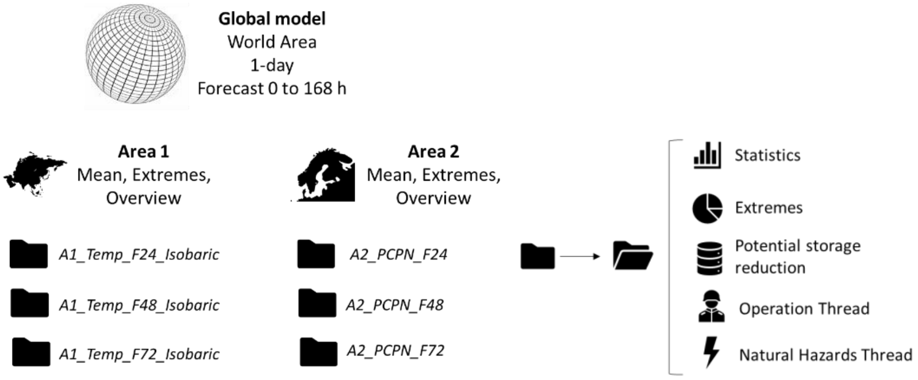


Figure 27. Schematic illustration depicting the processing of global data, their segmentation to optimize the query process, and automated evaluation of key features with the assignment of metadata

The initial step involves the comprehensive partitioning of domains and critical phenomena, a phase crucially driven by user requirements. Therefore, it may aptly be termed as user-needs-based. Typically, meteorological databases are organized according to the preferences of the founders, often misaligned with the actual data selection process. Consequently, this mismatch necessitates extensive subsetting, resulting in significant time consumption.

2.2. AI DATA CHECK

What sets the system apart from standard services is its capability for immediate real-time data evaluation. This evaluation encompasses conventional statistical methods like persistence check and range check [13], as well as advanced machine learning (ML) processes. These ML techniques are applicable to complex phenomena, human predictions, categorical variables, and intricate relationships such as wind direction and speed, cloud base and coverage, height of zero isotherm, and icing occurrence, among others [18].

Given the high volume of data involved, the system prioritizes computationally efficient methods such as logistic regression, isolation forest, and their combination to ensure the robustness of the evaluation process. These methods offer effective solutions without imposing excessive computational burden.

2.3. AI DATA PROCESSING

The initial forecast itself is closely linked to data control and can be automated. Upon receiving the first forecasts, which can extend over 300 hours ahead for global models, initial data derived from archive analysis becomes available:

1. The forecasted value,
2. Extremity (percentile of all historically forecasted values),
3. Probability of change and its direction.

This pre-processing approach is motivated by the fact that continuous monitoring of the initial predictions, characterized by high variance and frequent changes, is unnecessary. Instead, focus should be directed towards outputs derived from these initial values that are relevant to the user (Figure 28).

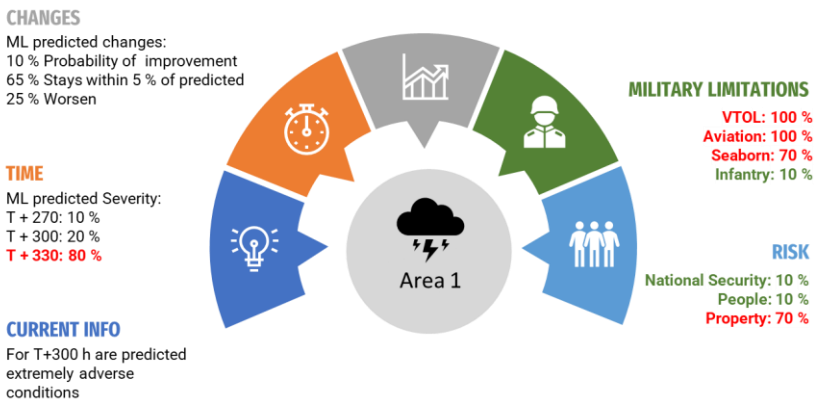


Figure 28. Schematic representation of the predicted value of the meteorological element in example Area 1 and its ML evaluation, development assumptions and predicted impacts on primary users

The real-time evaluation will involve assigning headers to the domain and its products, which will be stored in a separate file. These headers will offer a pre-processed summary of the current conditions at the site before specific requests are initiated. This fundamental information can be directly accessed from the database, thereby expediting queries and simplifying the development of specialized products.

2.4. ANALYSES AND PRODUCTS

By organizing the database and using pre-built analyses, developers and professionals can easily retrieve the data they need from pre-packaged data products and create specialized products for a variety of users (Figure 29).

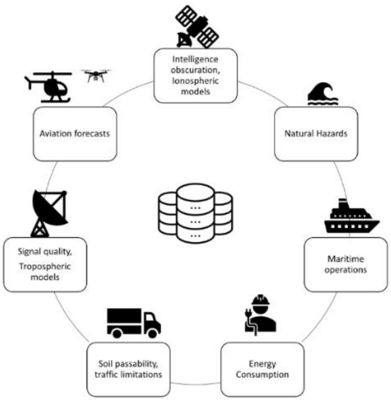


Figure 29. Segments of potential users and required products

Users typically have two primary questions regarding meteorological predictions:

1. Will conditions be favorable for my needs?
2. Can we trust the predictions?

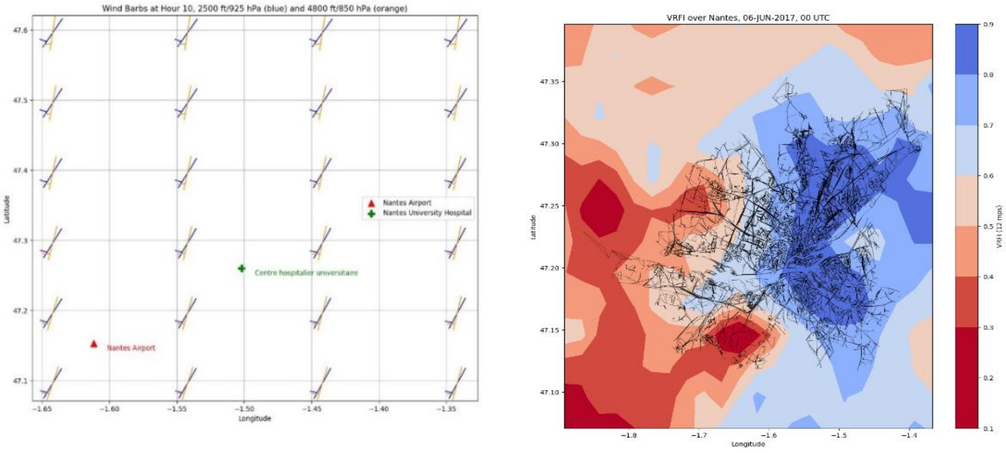
The proposed analyses aim to address these questions directly. To ensure clarity, the visualization of the proposed products prioritizes simplicity, ideally presenting information in the form of aggregated indices. These indices will capture various operational characteristics:

1. Essential to the operation: Unfavorable values indicate conditions that significantly impact operations, such as high wind speeds or hazardous events.

2. Mission assurance costs: Unfavorable values indicate conditions that result in high costs for mission assurance, such as energy-intensive flights or increased maintenance requirements.
3. Analytical: Unfavorable values indicate low predictability of the situation, where machine learning methods exhibit wide variations and cannot reliably predict outcomes.

These analytical indices play a crucial role in answering the second question, addressing the credibility of predictions for specific locations and situations.

As an example, consider the visualization for an airborne urban operation. In such scenarios, forecast clarity is paramount to ensure operational safety and efficiency. To address the specific requirements of airborne vehicle operations, where meteorological conditions and vehicle limitations are crucial considerations, a simplified visualization of standard Wind/Temperature charts is proposed. These maps can be converted into a generalized feasibility index adapted to a given operation and including its limit values. This index, tested in preliminary study, facilitates predictions while also accounting for the probability of predicted values changing over time using ML regression models based on the global and local model combination.



(a) (b)

Figure 30. Types of visualization of the wind information: (a) Current standard visualization using wind barbs, (b) Proposed visualization using Feasibility Index related to the vehicle limits. (Data: model AROME, Nantes)

A set of customized indexes and interpretation tools could assist each user in displaying a binary map that accurately represents their specific needs. This approach eliminates the need to decode various symbols or values, allowing users to directly assess the level of threat to their operations.

2.5. DATA STORAGE REDUCTION

When creating the database, it is necessary to include a plan for how the weather data can be reduced. While advances in computer science and data compression are remarkable, ML methods in particular can help in the storage of weather data [20], [21], [22], [23]. The vision entails optimizing data storage by leveraging ML models to represent ordinary data effectively. Instead of explicitly storing every dataset, the focus is on understanding which ML models can accurately represent the data and their associated errors based on existing predictors. Examples of such optimization strategies include:

1. Numerical models: Streamlining by reducing vertical levels, minimizing the number of grid points, or compressing time steps.
2. Image data: Employing techniques for efficient compression or representation.
3. General data: Utilizing alternative models, parameters, and error matrices to encapsulate information effectively while minimizing storage requirements.

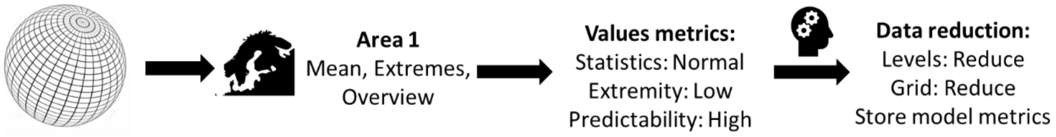


Figure 31. Global data processing, domain splitting, evaluation and data reduction on the example of normal, predictable and non-extreme data

When used for only a few areas of interest, a limited training dataset, or when deleting historical data, it is possible that the database requirements will not be demanding. However, if data should be stored globally, these strategies will need to be applied.

3. CONCLUSIONS

The challenges outlined in this paper underscore the critical need for innovative solutions in meteorological support. With decision-making processes in drone, airborne, artillery or vehicle operations heavily reliant on local models and observations, and the absence of a cohesive database hindering standardized decision-making, there is a clear imperative for transformative action.

To address these challenges, this paper advocates for the establishment of a comprehensive database tailored to the needs of defence and crisis management sectors. By providing readily accessible pre-built products, simplified indexes, and visualization procedures, this initiative aims to empower end-users with actionable insights in critical decision-making scenarios.

Future research should focus on connecting emerging technologies such as AI and the most advanced data sources to further improve the predictive capabilities of meteorological models. In addition, efforts to standardize data formats and foster collaboration between expert communities will be essential to harmonize knowledge and facilitate interoperability across different operational environments.

By embracing these forward-looking approaches, we can unlock the full potential of meteorological support, enabling more informed decision-making and better outcomes for military, civil protection, and humanitarian operations alike.

References

[1] COMMISSION IMPLEMENTING REGULATION (EU) 2023/138: laying down a list of specific high-value datasets and the arrangements for their publication and re-use. 2022.

[2] Horel, J., Splitt, M., Dunn, L., Pechmann, J., White, B., Ciliberti, C., Lazarus, S., Slemmer, J., Zaff, D., & Burks, J. (2002). MESOWEST: COOPERATIVE MESONETS IN THE WESTERN UNITED STATES. Bulletin of the American Meteorological Society, 83(2), 211-226. https://doi.org/10.1175/1520-0477(2002)083<0211:MCMITW>2.3.CO;2

[3] Lareau, N. P., Crosman, E., Whiteman, C. D., Horel, J. D., Hoch, S. W., Brown, W. O. J., & Horst, T. W. (2013). The Persistent Cold-Air Pool Study. Bulletin of the American Meteorological Society, 94(1), 51-63. https://doi.org/10.1175/BAMS-D-11-00255.1

[4] P. Nayna Schwerdtle, E. Irvine, S. Brockington, C. Devine, M. Guevara, and K. J. Bowen, “Calibrating to scale: a framework for humanitarian health organizations to anticipate, prevent, prepare for and manage climate-related health risks”, Globalization and Health, vol. 16, no. 1, 2020.

[5] P. Tatham and Nezih Altay, Q. Lu, M. Goh, and R. De Souza, “Learning mechanisms for humanitarian logistics”, Journal of Humanitarian Logistics and Supply Chain Management, vol. 3, no. 2, pp. 149-160, Oct. 2013.

[6] J. Jeuring, E. M. Samuelsen, M. Lamers, M. Müller, B. Å. Hjøllo, and L. Bertino, “Map-based ensemble forecasts for maritime operations: An interactive usability assessment with decision scenarios”, Weather, Climate, and Society, Feb. 2024.

[7] V. Rillo, A. L. Zollo, and P. Mercogliano, “MATISSE: an ArcGIS tool for monitoring and nowcasting meteorological hazards”, Advances in Science and Research, vol. 12, no. 1, pp. 163-169, 2015.

[8] V. Sreeja, “Impact and mitigation of space weather effects on GNSS receiver performance”, Geoscience Letters, vol. 3, no. 1, 2016.

[9] J. T. Abatzoglou, D. E. Rupp, L. W. O'Neill, and M. Sadegh, “Compound Extremes Drive the Western Oregon Wildfires of September 2020”, Geophysical Research Letters, vol. 48, no. 8, Apr. 2021.

[10] T. A. Gowan, J. D. Horel, A. A. Jacques, and A. Kovac, “Using Cloud Computing to Analyze Model Output Archived in Zarr Format”, Journal of Atmospheric and Oceanic Technology, vol. 39, no. 4, pp. 449-462, 2022.

[11] Gupta, T. and Roy, S. (2021). Recovery processes in coastal wind farms under sea-breeze conditions. Advances in Geosciences, 56, 129-139. https://doi.org/10.5194/adgeo-56-129-2021

[12] “Delivering the Digital European Sky,” SESAR Joint Undertaking | Delivering the Digital European Sky. [Online]. Available: https://www.sesarju.eu/. [Accessed: 13-Mar-2024]

[13] “Welcome to your ultimate resource for real-time and historical weather”, Synoptic Data, 02023. https://synopticdata.com/.

[14] “The Global Leader in Weather Intelligence | Meteomatics.” (2023) [Online]. Available: https://www.meteomatics.com/

[15] “Weather For The Automation Age-”, TruWeather Solutions, (2024). [Online]. Available: https://truweathersolutions.com/

[16] “Unisphere,” Unisphere. [Online]. Available: https://www.unisphere.de/

[17] “Homepage | Copernicus.” [Online]. Available: https://www.copernicus.eu/en

[18] K. Hubbard, J. You, and M. Shulski, (2012) “Toward a Better Quality Control of Weather Data”, Practical Concepts of Quality Control. InTech, Dec. 19 2012, doi: 10.5772/51632.

[19] Chatani, S. and Sharma, S. (2018). “Uncertainties caused by major meteorological analysis data sets in simulating air quality over India”. Journal of Geophysical Research Atmospheres, 123(11), 6230-6247. https://doi.org/10.1029/2017jd027502

[20] Lu, M., Chambliss, D., Glider, J., & Constantinescu, C. (2012). Insights for data reduction in primary storage: a practical analysis., 17. https://doi.org/10.1145/2367589.2367606.

[21] Kumar, A. (2004). “New Techniques for Data Reduction in a Database System for Knowledge Discovery Applications”. Journal of Intelligent Information Systems, 10, 31-48. https://doi.org/10.1023/A:1008633406999.

[22] Aha, D., Kibler, D., & Albert, M. (2004). ”Instance-based learning algorithms”. Machine Learning, 6, 37-66. https://doi.org/10.1007/BF00153759.

[23] Czarnowski, I. (2011). “Distributed Learning with Data Reduction”. Trans. Comput. Collect. Intell., 4, 3-121. https://doi.org/10.1007/978-3-642-21884-2_1.

TOWARDS SMALL OBJECT DETECTION IN SPACE: PHOTONIC INTEGRATED QUANTUM ILLUMINATION

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Abstract

This work proposes leveraging quantum mechanical properties for enhanced detection of faint space debris and potentially ill-intentioned small satellites. Central to our system is the design of a Photonic Integrated whispering gallery mode resonator (WGMR), utilizing thin film lithium niobate technology. This resonator serves as an optical–sub-terahertz entanglement source and frequency upconversion stage, ideal for space applications because of its reduced SWaP. Although quantum technologies may not yet be mature for immediate deployment, some expected advancements include improved sensitivity and precision, reduced noise levels, and increased reliability. Leveraging the features of Photonic Integrated WGMR and passive cooling, our design presents a compelling solution for the challenges of weak signal power detection. However, it is crucial to acknowledge that overcoming current limitations, such as achieving higher upconversion efficiency and enhancing the Q factor, requires continued research and development efforts.

Keywords

Quantum illumination, photonic integrated circuit, space debris, entanglement, frequency upconversion.

1. INTRODUCTION

Space debris represent a significant threat to satellites and spacecraft in Earth's orbit due to increasing congestion, raising the risk of collisions with potentially catastrophic outcomes. Monitoring CubeSats and small satellites is essential for security, given the surge in launches and the growing number of satellites, including those from potentially ill-intentioned actors. Accurate detection of both space debris and small satellites is crucial for defence applications; however, current detection methods face limitations due to factors such as debris volume and the size of objects being tracked.

The purpose of this paper is to outline an innovative approach to detecting faint space debris and small satellites by leveraging quantum mechanical properties, particularly the exploitation of entangled photons to enhance detection capabilities. Our objective is to achieve comprehensive coverage of the space environment through the integration of quantum and classical radar systems. The quantum detection component is specifically tailored to detect small debris and satellites at closer ranges, benefiting from heightened sensitivity and noise reduction. Meanwhile, the classical radar system complements this by detecting larger debris at greater distances.

Central to our proposed system is the design and characterization of a compact Photonic Integrated whispering gallery mode resonator, utilizing thin film lithium niobate (LiNbO3)

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technology, serving as an optical–sub-terahertz entanglement source and frequency upconversion stage, making it highly suitable for space applications like satellite deployment.

2. STATE OF THE ART

Existing space debris detection relies primarily on classical radar systems and optical telescopes. Ground-based radar systems, such as NASA's Haystack Ultrawideband Satellite Imaging Radar (HUSIR) and Goldstone Orbital Debris Radar (Goldstone), track larger debris in low Earth orbit (LEO) and geostationary orbit (GEO), providing data on debris ranging in size from approximately 5 mm to 2-3 cm in low Earth orbit (LEO). Optical telescopes, like the Eugene Stansbery Meter Class Autonomous Telescope (ES-MCAT), utilize visible or infrared light to observe space objects, effectively tracking larger debris and active satellites with high-resolution imaging capabilities [1].

In recent years, there has been growing interest in leveraging quantum technologies, such as quantum illumination, for defence applications, including space debris detection. Quantum illumination exploits quantum entanglement to improve sensitivity and reduce noise levels, offering enhanced detection capabilities compared to classical radar systems. Zhang et al. [2] demonstrated the first quantum illumination experiment in 2015 at optical frequencies, achieving a 20% improvement in detection error probability exponent compared to classical systems. Similarly, Assouly et al. [3] achieved a 20% performance enhancement over any classical system in 2023 at microwave frequencies.

Although quantum technologies may not yet be mature for immediate deployment in space debris detection, there's strong anticipation that quantum illumination could revolutionize the field. Expected advancements include improved sensitivity and reduced noise levels, enabling precise identification of space debris, even in cluttered environments where classical systems struggle. Quantum illumination also promises enhanced precision in determining object position and size, and increased reliability in adverse conditions. Mounting a quantum illumination system on a satellite can also provide a significant advantage, extending detection capabilities to distances unreachable by ground-based systems.

3. QUANTUM ILLUMINATION SYSTEM MODEL

The description of our proposed quantum radar system is based on Quantum Illumination (QI), a quantum protocol for target detection introduced by Lloyd [4]. This concept is graphically presented in Figure 1.

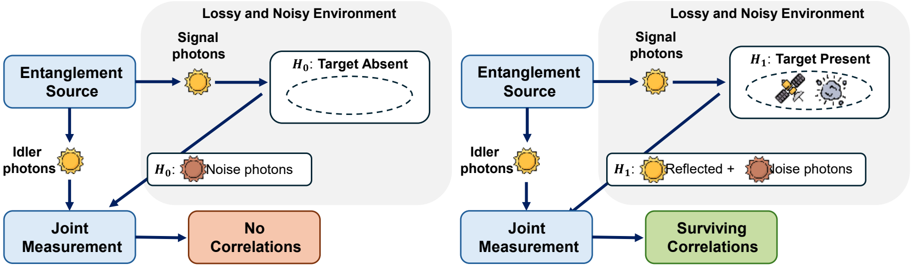

Figure 1. Quantum Illumination protocol. H_0*, target absent (left) and* H_1*, target present (right).*

QI involves generating a pair of entangled photons, typically called signal and idler, and sending the signal photon towards the target while retaining the idler as a reference. The transmitted photon is used to probe a distant region where a target may be suspected. If an object is present, the photon may be reflected and received along with the environmental noise photons;

otherwise, only noise photons will be detected. To gain an advantage over classical systems, each received photon must undergo a joint measurement with the idler photon. Even if entanglement is broken due to a lossy and noisy medium, surviving correlations provide information that can be used to probabilistically differentiate between two hypotheses H_0 (target absent) or H_1 (target present) when the process is repeated multiple times [5].

3.1. ELECTRO-OPTIC INTERACTIONS

To first comprehend the functioning of the entanglement source and upconversion stage further proposed, let's first study the interaction between an optical pump (ω_{pump}) and a sub-terahertz field (ω_{sT}) within a medium exhibiting nonlinear characteristics, such as lithium niobate, which will serve as the material for fabricating the photonic integrated circuit.

The nonlinear electro-optic effects induced by the material lead to the modulation of the optical field by the sub-terahertz field, resulting in the generation of two optical sidebands through the processes of Sum Frequency Generation (SFG) and Difference Frequency Generation (DFG) [6]. To enable the interaction between optical and sub-terahertz fields, it suffices to match the sub-terahertz frequency with the optical Free Spectral Range (FSR) of the resonator ($\omega_{sT} = FSR$). This ensures the phase-matching condition is met [7].

In Sum Frequency Generation (SFG), a sub-terahertz and an optical photon are combined to create an up-shifted photon at the sum frequency $\omega_S = \omega_{pump} + \omega_{sT}$, effectively upconverting the sub-terahertz signal into the optical domain. Ideally, the spectrum of this sideband aligns with the input sub-terahertz spectrum, facilitating accurate measurements of the sub-terahertz field once it transitions into the optical domain. On the other hand, in Difference Frequency Generation (DFG), a sub-terahertz photon can stimulate an optical pump photon to decay into a down-shifted optical photon at the difference frequency $\omega_D = \omega_{pump} - \omega_{sT}$, along with an additional sub-terahertz photon ω_{sT}. This process can occur spontaneously without the need for the sub-terahertz signal. This is called spontaneous parametric downconversion (SPDC) and it can be used to generate entangled pairs of sub-terahertz (signal) and optical (idler) photons [8]. We can employ the interaction Hamiltonian, assuming a strong optical pump, to further understand the interactions within the system:

$$\hat{H}_{int} = \hbar g_0 \sqrt{n_p}\left(\hat{a}_D^\dagger\, \hat{a}_{sT}^\dagger + \hat{a}_D \hat{a}_{sT}\right) + \hbar g_0 \sqrt{n_p}\left(\hat{a}_S^\dagger\, \hat{a}_{sT} + \hat{a}_S\, \hat{a}_{sT}^\dagger\right) \tag{1}$$

Where $\hbar$ is the reduced Planck's constant, g_0 the vacuum coupling rate, n_p represents the average number of pump photons, and $\hat{a}_D$, $\hat{a}_S$ and $\hat{a}_{sT}$ are the annihilation operators of the DFG, SFG, and the sub-terahertz modes, respectively.

The first segment, recognized as the two-mode squeezing term, denotes the annihilation of a pump photon, to create a down-shifted optical photon, and a sub-terahertz photon, representing the DFG process. This interaction can generate an entangled two-mode squeezed state between sub-terahertz and optical frequencies. The difference frequency mode will serve as the idler ($\omega_{idler} = \omega_D = \omega_{pump} - FSR$) and the sub-terahertz mode as the signal ($\omega_{signal} = FSR$).

The second segment, labelled the beam splitter term, indicates the annihilation of a pump and a sub-terahertz photon, resulting in an up-shifted optical photon ($\omega_{up} = \omega_{pump} + \omega_{sT}$) corresponding to the SFG process. It showcases an interaction similar to that of a beam splitter, where a photon is eliminated in one mode while another is produced in the other mode, conserving the photon number. As a result, this term can be utilized to transduce photons between modes fundamentally without introducing additional noise.

These two processes, shown in Figure 2, allow us to utilize the same device to generate entangled states and to upconvert the received sub-terahertz signal to the optical domain before the joint measurement. We can choose which process to employ by detuning the optical pump to higher or lower frequencies and matching the sub-terahertz mode to the new required frequency [7].

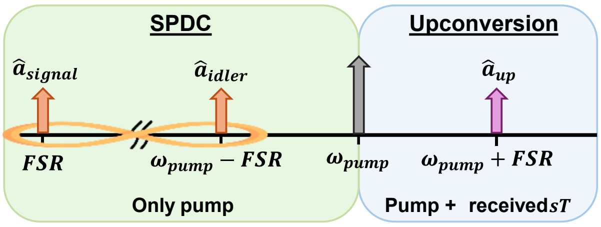

Figure 2. Entanglement generation and upconversion processes diagram in frequency domain.

3.2. OPTICAL– SUB-TERAHERTZ PHOTON ENTANGLEMENT GENERATION

For entanglement generation, we can detune the pump to a lower frequency, which suppresses the beam splitter interaction responsible for upconversion. Knowing that the thermal populations of the signal (N_{Sth}) and idler (N_{Ith}) modes depend on the modes' frequencies and temperatures according to Planck's thermal radiation equation $N_{j_{TH}} = \frac{1}{e^{\hbar\omega_j/k_B T} - 1}$ the two-mode squeezing interaction will produce an entangled two-mode squeezed thermal state with covariance matrix

$$V = \begin{bmatrix} N_S + {}^1\!/_2 & 0 & N_C & 0 \\ 0 & N_S + {}^1\!/_2 & 0 & -N_C \\ N_C & 0 & N_I + {}^1\!/_2 & 0 \\ 0 & -N_C & 0 & N_I + {}^1\!/_2 \end{bmatrix} \tag{2}$$

Where $N_S = 0.5 \times \left[\cosh(2r)\left(N_{S_{TH}} + N_{I_{TH}} + 1\right) + \left(N_{S_{TH}} - N_{I_{TH}}\right) - 1\right]$, $N_I = 0.5 \times \left[\cosh(2r)\left(N_{S_{TH}} + N_{I_{TH}} + 1\right) - \left(N_{S_{TH}} - N_{I_{TH}}\right) - 1\right]$, $N_C = 0.5 \times \sinh(2r)\left(N_{S_{TH}} + N_{I_{TH}} + 1\right)\cos(\phi)$, r is the squeezing parameter and ϕ the squeezing angle. If we consider working in vacuum conditions ($N_{Sth} = 0$ and $N_{Ith} = 0$), we will obtain an entangled two-mode squeezed vacuum state ($N_S = N_I$) [9], exhibiting the strongest entanglement. This indicates that the higher the frequencies and the lower the temperature, the stronger the entanglement achieved.

3.3. TARGET MODEL

The signal photons of the entangled state are employed to probe a region characterized by high losses and a significant thermal background. The objective is to differentiate between our two potential hypotheses, H_0 and H_1, which are assumed to have an equal a priori probability of 50%.

Under H_0, the signal photons are lost, and the radar receives only thermal noise represented as a thermal state with N_T average number of thermal photons. The covariance matrix between the idler and the received thermal photons is:

$$V_0 = \begin{pmatrix} N_T + 1/2 & 0 & 0 & 0 \\ 0 & N_T + 1/2 & 0 & 0 \\ 0 & 0 & N_I + 1/2 & 0 \\ 0 & 0 & 0 & N_I + 1/2 \end{pmatrix} \tag{3}$$

There are no off-diagonal elements in the covariance matrix, which means that there is no correlation between the idler and thermal photons [5].

Under hypothesis H_1, some of the signal photons interact with the target, leading to a blend of reflected photons and thermal noise, forming what we refer to as the return signal. The interaction with the target can be represented by a beamsplitter with extremely low reflectivity κ≪1. One input of the beamsplitter receives the signal, while the other receives a thermal state. The resulting covariance matrix for the idler-return signal is as follows:

$$V_1 = \begin{pmatrix} \kappa N_S + N_T + 1/2 & 0 & \sqrt{\kappa} N_C & 0 \\ 0 & \kappa N_S + N_T + 1/2 & 0 & -\sqrt{\kappa} N_C \\ \sqrt{\kappa} N_C & 0 & N_I + 1/2 & 0 \\ 0 & -\sqrt{\kappa} N_C & 0 & N_I + 1/2 \end{pmatrix} \quad (4)$$

The off-diagonal terms of the matrix are attenuated by the factor $\sqrt{\kappa}$. This reduction, resulting from losses and a noisy channel, may entirely disrupt the initial entanglement. However, the remaining correlations provide us with the chance to differentiate between hypotheses [5].

3.4. FREQUENCY UPCONVERSION AND PHASE-CONJUGATE RECEIVER

By detuning to a higher pump frequency, we can suppress the squeezing interaction. The beam splitter interaction facilitates the upconversion of the return photons to the optical domain with a certain efficiency. This enables the use of receivers reliant on photon counting, such as the phase-conjugate receiver proposed by Guha and Erkmen in [10] and shown in Figure 3.

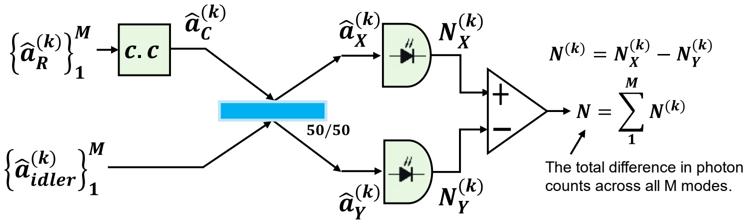

Figure 3. Phase-conjugate receiver [10].

This receiver conducts a joint measurement between the idler and return photons, providing up to a 3dB gain in the SNR compared to the optimal classical receiver when $N_S \ll 1$, $\kappa \ll 1$ and $N_T \gg 1$. Initially, it phase-conjugates the return modes received as $\hat{a}_C = \sqrt{2}\,\hat{a}_V + \hat{a}_R^{\dagger}$, where $\hat{a}_V$ is the vacuum state operator necessary to preserve the commutation relationships. Subsequently, the phase-conjugated signal is interfered with the idler mode in a 50/50 beam splitter, and both outputs are photon-counted and directed into a unitary gain difference amplifier, resulting in the final measurement $N = N_X - N_Y$. With repeated measurements, the number of photons obtained varies as a random variable that can be characterized by the mean and variance N_0 and ${\sigma_0}^2$ under H_0, and N_1 and ${\sigma_1}^2$ under H_1. If the number of entangled states generated M is sufficiently high, the distributions approximate Gaussian distributions with means and variances MN_j and $M{\sigma_j}^2$, respectively. This enables us to convert the problem of distinguishing between two quantum states into distinguishing between two Gaussian distributions using a threshold detector, where $N_{th} = \lceil M(\sigma_1 N_0 + \sigma_0 N_1)/(\sigma_1 + \sigma_0) \rceil$. The detector favors H_0 when $N < N_{th}$ and H_1 otherwise.

4. PIC DESIGN AND CHARACTERIZATION

The proposed LiNbO3 photonic integrated circuit was designed to accommodate a pump operating around a wavelength of 1550 nm and a return signal of 500 GHz to 1 THz, to reduce the thermal population as much as possible. It consists of two different subsystems, optical and sub-terahertz. The optical subsystem includes a bus waveguide, a 50 µm radius ring resonator (RR), and an asymmetric Mach–Zehnder interferometer (AMZI) with a path length imbalance of 250 µm between its two arms. The bus waveguide couples the optical pump to the ring resonator. The optical signal is required within the resonator to enable the generation of entangled pairs of sub-terahertz and optical photons, as well as the upconversion of incoming sub-terahertz photons. This coupling is achieved through evanescent field coupling between the bus waveguide and the cavity. Due to the high Q factor of integrated $LiNbO_3$ resonators, the operational bandwidth of the device is constrained to a few Megahertz (MHz). To increase the bandwidth of the device, a wavelength filter, based on an AMZI, is incorporated. This filter operates by extracting the generated photons in an overcoupled regime (wider resonance), while simultaneously reintroducing the pump into the optical resonator to maintain the highest power possible inside the resonator.

The sub-terahertz system comprises a microstrip antenna for capturing energy from the surrounding space, and a microstrip ring resonator (RR) for confining energy fields within the $LiNbO_3$ RR. Serving as a link between free space and the resonator, the antenna's role is to supply a stable field distribution within the RR.

In the first phase, a passive photonic integrated circuit (PIC) was fabricated. This was used to evaluate the optical elements of the system. Fabricated on a thin-film lithium niobate (TFLN) on-insulator platform, it comprised four AMZIs, each with different gaps between the waveguides of the directional couplers: $AMZI_1$: 0.65 µm, $AMZI_2$: 0.55 µm, $AMZI_3$: 0.45 µm and $AMZI_4$: 0.35 µm. The objective was to determine the gap that yielded a 50/50 splitting ratio in the directional couplers. Additionally, the PIC included eight ring resonators (RRs), each with a varied gap between the input waveguide and the resonator: RR_1: 1.4 µm, RR_2: 1.26 µm, RR_3: 1.11 µm, RR_4: 0.97 µm, RR_5: 0.829 µm, RR_6: 0.686 µm, RR_7: 0.543 µm and RR_8: 0.4 µm. This variation aimed to characterize the transmission spectrum of the resonator relative to the gap.

The second phase involved the fabrication of the complete system in a PIC, therefore, including now the sub-terahertz subsystem. Six structures were fabricated, adjusting the gap between the bus waveguide and resonator, as well as the gap in the directional couplers, around the optimal values determined in the prior fabrication round. This second PIC has yet to undergo characterization; hence, in this manuscript, we only present the characterization results of the first PIC. In Figure 4 we illustrate the design of the complete system, the footprint of the PIC compared to a coin, alongside microscope images of the first and second photonic integrated circuits.

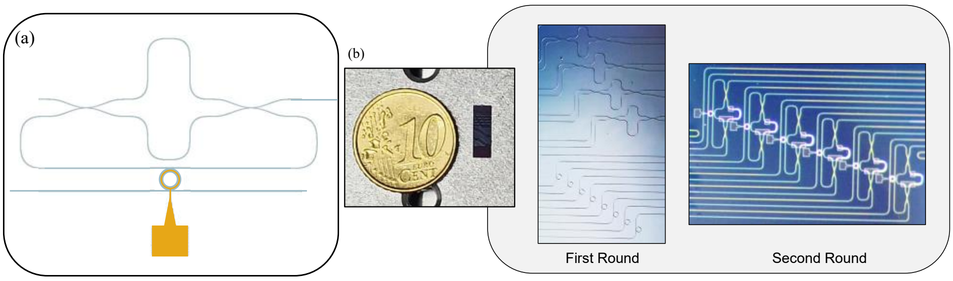

Figure 4. (a) PIC design and (b) microscope images of the first and second fabrication rounds.

In Figure 5, we present the measurements of the most effective structures, namely $AMZI_3$ and resonators six, seven and eight. Figure 5 (left) illustrates the optical response obtained at both arms of the interferometer when light is injected through its top input arm. We achieved an extinction ratio (ER) of 25 dB and a Free Spectral Range (FSR) of 662.5 ± 37.5 GHz. The ER achieved ensures that minimal pump power appears at the output port along with the generated sidebands, ensuring that almost all the pump power is reinjected into the cavity. The FSR matches the frequency range of our intended application. Figure 5 (right) shows the transmission spectrums of resonators RR_6, RR_7 and RR_8. From these results we can conclude that the optimum gap between the input waveguide and the ring resonator is around 0.543 µm (RR_7) due to its flat spectrum. By performing a Lorentzian fit, we estimate an intrinsic quality factor of $Q = 10^5$.

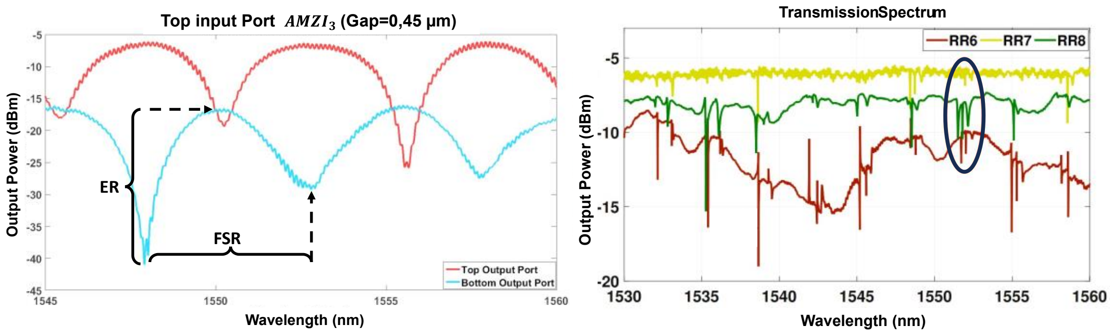

Figure 5. Espectral response of $AMZI_3$ (left) and RR_6, RR_7 and RR_8 (right).

5. QUANTUM ILLUMINATION DETECTION SYSTEM

In Figure 6 we illustrate a block diagram outlining the design and expected operation. Step 1 involves pumping with a detuned-down pump to suppress beamsplitter interaction. This pumping will generate pairs of entangled photons via SPDC, obtained at point 2. The idler photons must be stored in a structure with minimal losses, such as a resonator or low-loss delay line, while the signal photons are transmitted to probe a section of space. If a target exists, the photons may reflect and be received by the antenna along with thermal noise from the environment, as indicated in step 3. At this point, the pump will switch to a detuned-up position to suppress squeezing operation. This pump will enable the upconversion of received photons to the optical spectrum. The upconverted photons obtained at point 5 are then sent along with the stored idler photons to point 6, the phase-conjugate receiver, where they interfere with each other and are then photon counted to ultimately obtain statistics providing information about our potential target.

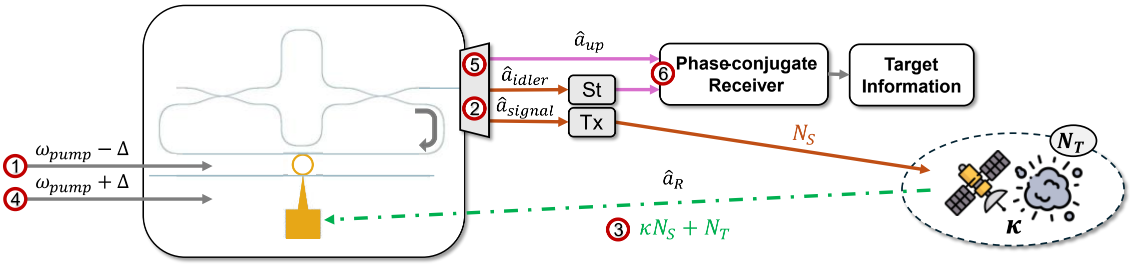

Figure 6. Block diagram of full PI small object detection system based on QI.

6. CONCLUSION

The goal of this research is to outline a design for a quantum illumination small object detection system with particular focus on the design of a photonic integrated whispering gallery mode resonator, utilizing thin film lithium niobate that would work as a sub-terahertz-optical photons entanglement source as well as a frequency upconversion stage for the received photons. Utilizing a whispering gallery mode PIC allows for an extended interaction time with the nonlinear material without requiring an excessively large crystal, thus ensuring lower losses. Furthermore, employing a resonator scheme enables higher levels of intracavity power compared to the pump power and facilitates a reduction in SWaP (size, weight, and power consumption). These characteristics make this design highly appealing for spaceborne applications, as it offers a compact SWaP profile, simplified connectivity, and minimal power demands. Notably, quantum illumination proves advantageous only in scenarios characterized by weak signal power, which is crucial for spaceborne applications where power is a limited resource. Another key characteristic of this design is radiative passive cooling. This effect occurs because the signal and the noise travel in different directions inside the resonator, allowing only the signal of interest to be upconverted. Consequently, this lowers the effective temperature of the resonator below its physical temperature, potentially enabling applications without the need for cryogenics [6].

One crucial current limitation of this application is the efficiency of the various processes involved. A near 100% upconversion efficiency is essential for optimal performance. Additionally, it is imperative to enhance the Q factor to maximize the production of entangled photon pairs per second. Currently, significant research efforts are focused on reducing losses and enhancing fabrication procedures to increase the Q factor. Moreover, another critical area of research involves developing an idler storage solution that must be as lossless as possible.

In conclusion, the design outlined in this research holds promise for advancing the capabilities of small object detection using quantum illumination, particularly in spaceborne applications where power efficiency and compactness are crucial. Leveraging the features of photonic integrated whispering gallery mode resonators and passive cooling, this design presents a compelling solution for addressing the challenges of weak signal power detection. However, it is crucial to acknowledge that overcoming current limitations, such as achieving higher upconversion efficiency and enhancing the Q factor, requires continued research and development efforts.

References

[1] A. Manis, J. A. Arnold, J. Murray, B. Buckalew, C. Cruz, y M. Matney, “An overview of ground-based radar and optical measurements utilized by the Nasa Orbital Debris Program Office”, 2nd International Orbital Debris Conference (IOC II), 2023.
[2] Z. Zhang, S. Mouradian, F. N. C. Wong, y J. H. Shapiro, “Entanglement-enhanced sensing in a lossy and noisy environment”, Phys. Rev. Lett., vol. 114, num. 11, 2015.
[3] R. Assouly, R. Dassonneville, T. Peronnin, A. Bienfait, y B. Huard, “Quantum advantage in microwave quantum radar”, Nat. Phys., vol. 19, num. 10, pp. 1418–1422, 2023.
[4] S. Lloyd, “Enhanced sensitivity of photodetection via quantum illumination”, Science, vol. 321, num. 5895, pp. 1463–1465, 2008.
[5] G. Sorelli, N. Treps, F. Grosshans, y F. Boust, “Detecting a target with quantum entanglement”, IEEE Aerosp. Electron. Syst. Mag., vol. 37, num. 5, pp. 68–90, 2022.
[6] G. A. S. Botello, “Low noise thz detection via optical parametric upconversion”, Universidad Carlos III de Madrid, Spain, 2021.
[7] Sahu, Rishabh. “Cavity Quantum Electrooptics.” Institute of Science and Technology Austria, 2023.

[8] A. Rueda et al., “Efficient microwave to optical photon conversion: an electro-optical realization”, Optica, vol. 3, num. 6, p. 597, 2016.
[9] S. Barzanjeh et al., “Stationary entangled radiation from micromechanical motion”, Nature, vol. 570, num. 7762, pp. 480–483, 2019.
[10] S. Guha y B. I. Erkmen, “Gaussian-state quantum-illumination receivers for target detection”, Phys. Rev. A, vol. 80, num. 5, 2009.

SPACEGUARD: HOW SPACE LAW ENFORCEMENT CAN ENHANCE SPACE SECURITY THROUGH COMPREHENSIVE MONITORING AND RESPONSE TO THREATS

M. Maestrini[1], N. Faraco[1], M. A. De Luca[1] and P. Di Lizia[1]

Abstract

The proliferation of space activities brought under the spotlight the urgent need for a robust space governance framework capable of enforcing laws, preventing illicit activities, and providing emergency response and support services. However, the absence of a dedicated space law enforcement agency has left a critical gap. In this paper, we propose an innovative end-to-end solution designed to address this challenge. Our approach focuses on the identification and characterization of unknown and potentially hostile space objects, including the determination of ownership and activities. Moreover, we highlight the dual-use nature of this solution, emphasizing its potential for commercial applications, particularly in on-orbit servicing. By leveraging existing technologies and fostering collaboration between public and private sectors, our framework offers a promising path towards enhancing space security and resilience in the face of evolving threats.

Keywords

Space Law Enforcement, On-orbit servicing, Artificial Intelligence, Navigation, Dual-use technology

1. INTRODUCTION

On Dec. 1, 2021, Gen. David Thompson, Vice Chief of Space Operations at Space Force, stated that U.S. satellites are being attacked by adversaries every day in ways that are nothing short of “acts of war”, and that the U.S. will lose the space arms race if they do not act immediately. The most common form of these attacks is reversible: they do not permanently damage the satellites (e.g., lasers, radio frequency jammers, and cyber-attacks). More recently, however, U.S. company LeoLabs [1] has shed light on even more troubling behaviours exhibited by certain non-EU countries (i.e., Russia and China). Notably, these countries have been conducting potentially threatening on-orbit activities that were timed to coincide with U.S. holidays, when fewer American skywatchers are vigilant. An example of this occurred on U.S. Thanksgiving 2023, when Russia’s Cosmos 2570 satellite revealed itself to be a satellite carrier consisting of three consecutively smaller objects engaged in proximity operations around each other. This event mirrored the behaviour of Cosmos 2565, an electronic reconnaissance satellite launched during the same period in 2022, which had released a daughter satellite (Cosmos 2566), followed by its own sub-satellite on Christmas Eve. Similarly, on Thanksgiving Day 2022, China’s Test Spacecraft 2 was observed conducting rendezvous and proximity operations that included a docking manoeuvre by a satellite it had released. While the purpose of these child satellites remains unclear, sub-satellite deployments can serve as a method for deploying co-orbital

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ASATs or covert payloads, posing potential risks to sensitive or classified satellites. The strategic timing of these manoeuvres can allow them to evade detection for extended periods, granting adversaries a significant advantage in potential conflicts. In essence, undetected satellite manoeuvres effectively conceal secret payloads in space until they are discovered, providing a window of opportunity for clandestine activities. European assets are not immune to such threats; therefore, it becomes a pressing matter to try to address the issue.

With the current capabilities, the only viable option in case a hostile agent approaches a European asset is to monitor the situation via ground sensors. However, the timeliness of these observations is subject to the constraints of visibility windows and weather conditions. Moreover, in case of extremely close approaches, ground sensors may lack the resolution to distinguish the hostile agent from the European asset. Besides, this monitoring does nothing in terms of protection. In short, there is no such thing as a Space Law Enforcement that can prevent illicit activities and provide an emergency response in case of a direct attack. The ability to respond with a non-destructive action (i.e., inspect the threat directly in space rather than neutralizing it with an ASAT) could help avoid unnecessary creation of debris while also deescalating situations of conflict, hence granting more time for on-ground crisis management. This paper proposes a novel approach to tackle this issue by relying on state-of-the-art methods for guidance and navigation about uncooperative and unknown targets.

The dual-use nature of these techniques is intrinsic: originally developed within the realm of space debris remediation methods to address the challenge of Active Debris Removal (ADR), they have garnered attention from commercial entities in recent years. Companies seek to capitalize on these techniques for On-orbit Servicing (OOS) endeavours, with the notable example being the MEV-1 vehicle servicing the Intelsat-901 satellite [2], showcasing their potential in extending the operational lifetime of satellites.

This paper will present SpaceGuard, a software designed to enable autonomous guidance and navigation in the proximity of an unknown and uncooperative object. Comprising three main building blocks (guidance, navigation, and capabilities identification) this technology is essential for achieving Space Law Enforcement objectives. In particular, the identification of capabilities is crucial for determining the owner of unidentified threats and assets and holding them accountable for any illegitimate action. In the following sections a review of the state of the art will be provided, as well as some preliminary results obtained by the authors. In conclusion, the competitive advantages that the EU could gain by becoming the first mover in this field will be discussed.

2. STATE OF THE ART OVERVIEW

Space Law Enforcement requires the capability of approaching and inspecting an unknown and uncooperative object in close proximity. This challenge can be readily tackled with technologies that are being developed to mitigate the issue of space debris such as ADR or OOS. This latter technique is gaining traction due to its commercial viability (expected 4 billion € cumulative revenue by 2028 [3]). Therefore, it is attracting significant investments from both space agencies (e.g. ESA's ADRIOS) and commercial entities. While originally intended for GEO fleet maintenance, OOS presents a lucrative, untapped market in the LEO environment, particularly with the rise of mega-constellations. To effectively carry out ADR and OOS tasks, specialized guidance and navigation techniques are essential to ensure safe operations. Therefore, by becoming the first to raise the technology readiness level (TRL) of such solutions, the EU can gain not only a strategic advantage in terms of military capabilities, but also for what concerns commercial activities.

In the most basic approaches for inspection of a Resident Space Object (RSO), the operator aims at minimizing the cost of manoeuvres. In such scenarios, trajectories can be designed through several techniques including manual design [4], but they inevitably lead to suboptimal performances and can easily fail to perform the task when the target's attitude impairs visibility. If a more thorough inspection is sought, it is necessary to introduce assumptions about an inspection metric, which inevitably involves the target's attitude. In these cases, the main driver for the design of guidance and navigation methods is the level of cooperativeness of the target and the a priori knowledge of its shape and inertia parameters.

In past missions and studies on OOS, it has been customary to assume completely known and actively cooperative targets; guidance and navigation techniques for such scenarios are tailored to one specific task and rely heavily on active communication links [5], (e.g., missions from the Apollo program, servicing flights of the Space Shuttle, assembly, and supply of the space station). In more general cases, the target is passively cooperative thanks to the presence of a small number of easily identifiable fiducial markers on its surface [6]. Several guidance techniques have been proposed in this case [4], with notable examples such as: NASDA's ETS-VII mission, AFRL's XSS-10/11, NASA's DART, Orbital Express, and Seeker-1 missions, and SSC's PRISMA mission. Their main downside is the detection and matching of markers from measurements, a step which is often taken for granted despite severely impairing convergence if the wrong correspondences are found [7].

By completely removing any form of cooperation from the RSO, but still assuming a priori knowledge of the target's geometric appearance, model-based methods such as Convolutional Neural Networks (CNN) [7] and point cloud registration like Iterative Closest Point (ICP) algorithm [8] can be used. For these methods it is more difficult to find correct correspondence between the measurements and the model due to the absence of fiducial markers. In these cases, the design of relative trajectories to the target has been performed through Motion Planning algorithms [9]. These guidance techniques have been developed in the field of autonomous driving and represent robotics' industry standard thanks to their low computational demand, which makes them suitable for implementation on limited-resource systems. However, these methods cannot explicitly deal with the uncertainties of the target's pose estimation.

Despite the variety of presented approaches, all the above-mentioned examples rely on some sort of cooperativeness and/or knowledge of the target (e.g. fiducial markers or accurate geometrical models) which is leveraged to plan proximity operations. Hence, none of these methods can deal with an RSO that is uncooperative and whose shape and properties are unknown. This situation may happen for many different reasons, which include the lack of disclosure of information from a hostile owner, but it may also be as simple as a change in configuration or damage (e.g., owed to collisions, explosion of internal tanks, etc.). In this challenging scenario, no active inspection trajectory design technique exists in literature. Therefore, the guidance would be determined by operators that gather data from the space segment, elaborate it on ground to determine the target's attitude and transmit commands to be executed to carry out an inspection. This approach increases the effort spent by mission analysts, reduces the timeliness due to the need of operating only during visibility windows, and increases the risk of human-induced errors: indeed, autonomous operations have been identified by NASA as a key enabling technology for next-generation space missions [10]. In this challenging scenario the chaser must operate by computing its trajectory while simultaneously building a model of the RSO. The state-of-the-art approach to tackle this problem is represented by Simultaneous Localization and Mapping (SLAM). Several examples exploiting particle filters and Extended Kalman Filter are available in literature [11]. However, the computational cost of these methods owed to features matching and filter steps grows with the size of the reconstruction, hence requiring a trade-off between computational cost and accuracy [12]. Moreover, to deal with an unknown and tumbling RSO, it is not sufficient to retrieve the relative pose with a navigation filter, but it is also necessary to recover inertia properties of this target.

The primary objective of this paper is to present the SpaceGuard approach, which offers a comprehensive solution for addressing the complexities of inspecting unknown and uncooperative targets through an integrated framework encompassing guidance, navigation, and capabilities identification. The discussion will begin with an overview of the overall strategy developed. This will rely on a guidance module that leverages the relative navigation suite to perform optimal inspection manoeuvres. During the inspection, the geometric shape and inertial properties of the target will be reconstructed. Moreover, the onboard system will leverage CNNs to identify key components of the target. This information can help define a new flight profile for the chaser around the target, to get more beneficial views on the most uncertain components of the inspected RSO. Finally, Sec. 4 will present the conclusion of this study and possible ways forward.

3. OVERVIEW OF SPACEGUARD

The proposed method to achieve guidance and navigation about any unknown and uncooperative RSO is described in this section. The approach relies on three main building blocks that are linked by the sequence of operations. Moreover, all three blocks share the same 3D sensor for operations (i.e., a stereo-camera), hence providing a cost-effective solution also in terms of mass and power budget.

First, the geometry reconstruction module is presented. This module oversees the reconstruction of the geometric 3D shape of the target during a preliminary analysis when no information is available. The built 3D model acts as an input of the second module: target characterization. This second building block includes the navigation system (in charge of characterizing the inertia parameters of the target) and the CNN used to identify critical components of the target satellite. Subsequently, the information extracted by this second module is provided to the final component of the algorithm: the guidance subsystem. This block exploits the relative pose estimate and the 3D coarse reconstruction of the target to provide a trajectory that optimizes information collection. In turn, the new information collected by the navigation system while following the new trajectory is used to update the 3D model of the target. An overview of the entire process is provided in Fig. 1. In the remainder of this paper, a summary of the main building blocks and some attainable results are presented.

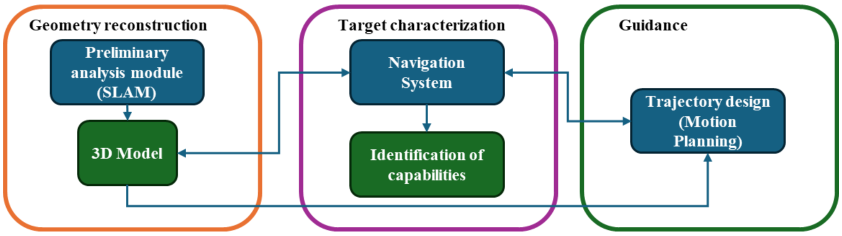

Figure 32: Overall scheme of the SpaceGuard.

3.1. GEOMETRY RECONSTRUCTION

This module requires the satellite to be placed in a passively safe relative trajectory around the target. During this phase, ORB-SLAM [12] is employed to build a geometric representation of the target. In [13] the authors of the present paper demonstrated the results that can be achieved by leveraging this approach. An example is reported in Fig. 2, where a frame of the SLAM run is reported together with the final reconstructed trajectory and geometric shape of the target.

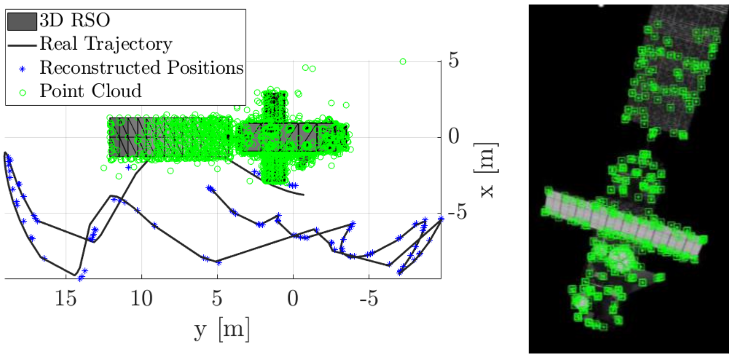

Figure 2: SLAM frame and final output of the reconstruction.

Once the model of the target has been built, it can be refined and postprocessed using principal component analysis and visibility constraint to retain a coarse model usable by the other modules of SpaceGuard.

3.2. TARGET CHARACTERIZATION

In this second phase, the focus is shifted from building the 3D model of the RSO to providing relative state predictions and estimating the inertia parameters of the target through sequential filtering. The navigation subsystem was first proposed by the authors of this work in [13], and a thorough outline of the process is provided in Fig. 3. At each measurement step, the point cloud extracted from the sensor suite is matched to the coarse on-board model with a point set registration technique that provides the relative pose. The selected registration method is called Bayesian Coherent Point Drift (BCPD) [14], which is a generalization of the ICP algorithm that matches the point clouds in a statistical sense, hence overcoming the issue of finding exact features correspondences. Moreover, this algorithm is more robust against noisy data and guarantees convergence in a finite number of iterations thanks to Bayesian Inference. The pose estimated by BCPD is fed to two separates Unscented Kalman Filters that oversee the reconstruction of relative state and attitude (including inertia parameters) respectively. The effectiveness of the approach in reconstructing the relative state and inertia properties of an unknown target has been demonstrated by the authors in [13]. Moreover, it was proven that the algorithm can run in real time also on a limited resource system, which makes the approach particularly appealing for usage on satellites that have notoriously few computing resources.

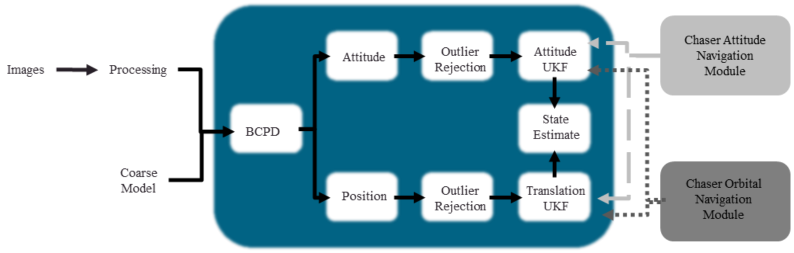

Figure 3: Complete outline of the navigation filter.

Aside from the target's inertial properties, its capabilities also need to be determined. To tackle this issue, the authors of this manuscript proposed in [15] a way to perform visual inspection of unknown RSOs through CNNs. In particular, the images of the target acquired by the onboard sensor suite are processed to identify the exact placement of components on the satellite as illustrated in Fig. 4. The pixel level information provided may turn out to be paramount for the determination of attitude, geometrical properties, and mass distribution of the observed object. Mask RCNN [16], which is the state-of-the-art algorithm for semantic segmentation using a dual stage approach, is leveraged in this work. Among its key innovations, this work also introduces an approach to obtain training data for such CNNs. To do this, the use of 3D models of various satellites is explored to programmatically generate images with different points of view and lighting conditions. This has been achieved through the open-source computer graphic software Blender, accurately scripted to generate images and the associated training labels automatically. By training on several different target objects, the CNN became capable of generalizing its predictions to unknown targets that are not included in the training data.

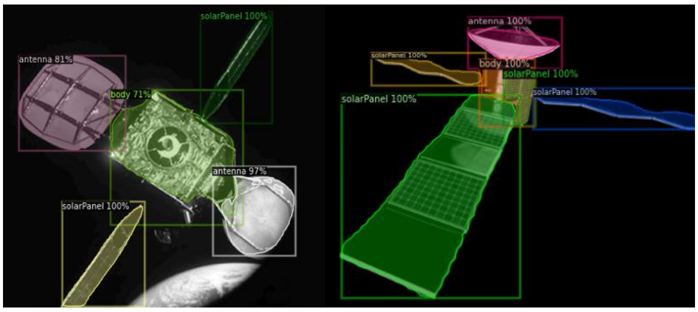

Figure 4: Identification of components from real (left, images from the MEV-1 mission) and synthetic (right) images.

3.3. GUIDANCE MODULE

The guidance module is tasked with providing a trajectory to collect the most information about the target. A method to perform this feat in presence of a completely unknown and uncooperative target is proposed [17]. This technique relies on a sampling-based receding-horizon algorithm to plan inspection. The proposed algorithm represents the most general case of satellite motion planning for inspection under relative state uncertainties, as it removes any assumption on the RSO's shape and tumbling motion. Moreover, the resulting guidance strategy can be suited to both on-board autonomous manoeuvre selection and offline trajectory design. To tackle the problem, the algorithm relies on Sampling Based Model Predictive Control [9] (SBMPC) as it can easily include black box constraints, and it is robust to uncertainties thanks to the periodic re-planning of manoeuvres. To this aim, it leverages the 3D shape of the object (provided by geometry reconstruction module) and the uncertain knowledge of the relative state (given by the target characterization module) to build a score function that aims at promoting exploration of unseen regions of the target. To do so, a 3D pseudo-density is computed. An example of this density function is illustrated in Fig. 5. In [17] the authors of this work proved the effectiveness of the approach also in comparison to standard approaches, and an example trajectory is also reported in Fig. 5. The obtained trajectory satisfies by construction all operative constraints including thruster limitations, passive safety, slew-rate limitations, and illumination conditions.

While following the newly designed trajectory, the target characterization module continuously updates the estimates of the target's structural components and the relative pose and uncertainty. Moreover, it also feeds the geometry reconstruction module with new images of the target to update the 3D geometric reconstruction, which is in turn leveraged by the guidance module, effectively closing the Guidance and Navigation loop and enhancing the knowledge of the alleged menace.

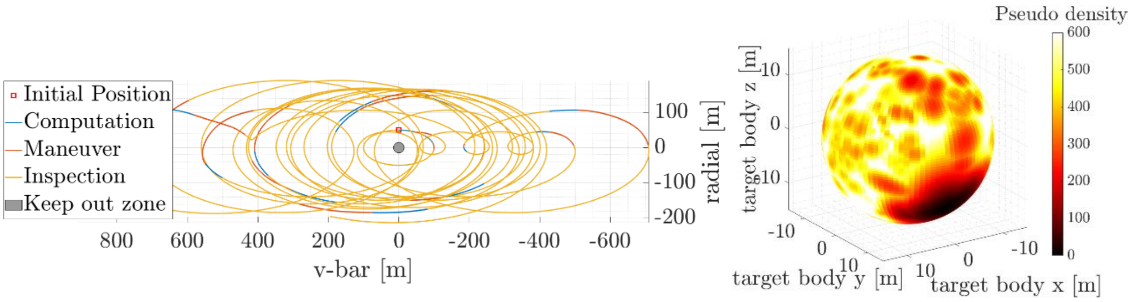

Figure 5: Complete guidance strategy (left) and 3D density function to rate trajectories (right).

4. CONCLUSIONS

In conclusion, the implementation of the SpaceGuard system represents a strategically viable and technically feasible endeavor. The key elements required for its establishment have already been developed from the founding principles up to a TRL 3, as evidenced by the various papers published on the subject by the authors. Thanks to the dual-use nature of this technological solution, OOS and ADR missions will provide opportunities to test some of the involved technologies, hence raising the TRL in the coming years. As an example, JAXA's ADRAS-J was launched in February 2024, whereas ESA's ClearSpace-1 and eInspector as well as UK's COSMIC are all set to launch before 2026. With an estimated 18 months for integration and testing of key processes for SpaceGuard on hosting missions, the key elements of the approach proposed in this paper could be raised from TRL 3 to 5 well before 2030. Conversely, a dedicated demonstrator for SpaceGuard is expected to have a total cost of 50 million €, 10% of which should be imputed to the cost of launch. The estimated costs are in line with similar missions such as ClearSpace-1 and ADRAS-J, despite being slightly reduced as SpaceGuard does not need the hardware to perform OOS or ADR. The mission is expected to have a favourable cost-value ratio thanks to the high level of automation of the procedures, thus reducing time, cost, and human error. In addition, potential savings are expected in case SpaceGuard is adopted and developed to a full-scale mission due to the possibility of avoiding costly space accidents. Moreover, encouraging European firms to develop these technologies would allow the EU to tap into the 4 billion € cumulative revenue [3] for their commercial application. Both the predicted timeline and estimated costs justify, therefore, the practical realizability of this initiative.

Regarding the military viability of the technology, its application in inspecting unknown and uncooperative objects in close proximity is very promising, especially in view of the establishment of Space Law Enforcement, which would fill a crucial capability gap not only for EU defence, but on a global scale. An orbital surveillance satellite will enable fast detection and identification of potential threats, such as anti-satellite weapons, hostile satellites, and space debris, along with their origins. Consequently, a European military space command equipped with this technology will be able to formulate effective response strategies, safeguarding national space assets. Once SpaceGuard capabilities are unlocked, the most critical assets of the EU satellite fleet could be endowed with them, so that each asset can monitor its own proximity. This possibility would shorten even more the response times needed for detection and identification of threats, and it is a possibility already under consideration by the EDA Cat. B project ASSAI and by the research actions for protection of space-based assets funded by EDF in 2023. Furthermore, the employment of this system fosters collaboration with allied space forces and international partners, enhancing collective space situational awareness, coordination, and response capabilities, strengthening alliance cohesion and interoperability. In the face of evolving security challenges, the proposed system represents, therefore, a proactive and prudent step to safeguard national and super-national interests and to ensure continued access to space for peaceful purposes.

References

[1] T. Hitchens, “LeoLabs: Russia, China time suspicious space activity for some US holidays.” breakingdefence.com. https://breakingdefence.com/2023/12/leolabs-russia-china-time-suspicious-space-activity-for-some-us-holidays/ (accessed Mar. 25, 2024)

[2] Northrop Grumman press release, “Northrop Grumman and Intelsat Make History with Docking of Second Mission Extension Vehicle to Extend Life of Satellite.” news.northropgrumman.com. https://news.northropgrumman.com/news/releases/northrop-grumman-and-intelsat-make-history-with-docking-of-second-mission-extension-vehicle-to-extend-life-of-satellite (accessed Mar. 25, 2024)

[3] A. Agrum, "NSR report forecasts $4.5 billion in cumulative revenues from in-orbit satellite services by 2028." nsr.com. https://www.nsr.com/nsr-report-forecasts-4-5-billion-in-cumulative-revenues-from-in-orbit-satellite-services-by-2028 (accessed Mar. 25, 2024)

[4] D. Zimpfer, P. Kachmar, and S. Tuohy, “Autonomous Rendezvous, Capture and In-Space Assembly: Past, Present and Future,” in Proc. 1st Space Exploration Conference: Continuing the Voyage of Discovery, 2005, pp. 234–245.

[5] J. Christian, S. Robinson, C. D’Souza, and J. Ruiz, “Cooperative Relative Navigation of Spacecraft Using Flash Light Detection and Ranging Sensors,” Journal of Guidance, Control, and Dynamics, vol. 37, no. 2, pp. 452–465, 2014.

[6] D. Woffinden, and D. Geller, “Relative Angles-Only Navigation and Pose Estimation for Autonomous Orbital Rendezvous,” Journal of Guidance, Control, and Dynamics, vol. 30, no. 5, pp. 1455–1469, 2007.

[7] M. Piazza, M. Maestrini, and P. Di Lizia, “Monocular Relative Pose Estimation Pipeline for Uncooperative Resident Space Objects,” Journal of Aerospace Information Systems, vol. 19, no. 9, pp. 613–632, 2022.

[8] R. Opromolla, G. Fasano, G. Rufino, and M. Grassi, “Pose Estimation for Spacecraft Relative Navigation Using Model-Based Algorithms,” IEEE Transactions on Aerospace and Electronic Systems, vol. 53, no. 1, pp. 431–447, 2017.

[9] F. Capolupo, and P. Labourdette, “Receding-Horizon Trajectory Planning Algorithm for Passively Safe On-Orbit Inspection Missions,” Journal of Guidance, Control, and Dynamics, vol. 42, no. 5, pp. 1023–1032, 2019.

[10] J. A. Starek, B. Açıkmeşe, I. Nesnas, and M. Pavone, “Spacecraft Autonomy Challenges for Next Generation Space Missions,” in Advances in Control System Technology for Aerospace Applications, ser. Lecture Notes in Control and Information Sciences, E. Feron, Ed. Springer, Sep. 2015, vol. 460, Ch. 1, pp. 1–48.

[11] V. Capuano, K. Kim, A. Harvard, and S. Chung, “Monocular-Based Pose Determination of Uncooperative Space Objects,” Acta Astronautica, vol. 166, Jan., pp. 493–506, 2020.

[12] M. Dor, and P. Tsiotras, “ORB-SLAM Applied to Spacecraft Non-Cooperative Rendezvous,” in Proc. 2018 Space Flight Mechanics Meeting, 2018, pp. 1963-1980.

[13] M. Maestrini, M. De Luca, and P. Di Lizia, “Relative navigation strategy about unknown and uncooperative targets,” Journal of Guidance, Control, and Dynamics, vol. 46, no. 9, pp. 1708-1725, 2023.

[14] O. Hirose, “A Bayesian Formulation of Coherent Point Drift,” IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 43, no. 7, pp. 2269-2286, 2020.

[15] N. Faraco, M. Maestrini, and P. Di Lizia, “Instance segmentation for feature recognition on non-cooperative resident space objects,” Journal of Spacecraft and Rockets, vol. 59, no. 6, pp. 2160-2174, 2022.

[16] K. He, G. Gkioxari, P. Dollár, and R. Girshick, “Mask R-CNN,” IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 42, no. 2, pp. 386–397, 2020.

[17] M. Maestrini, and P. Di Lizia, “Guidance strategy for autonomous inspection of unknown non-cooperative resident space objects,” Journal of Guidance, Control, and Dynamics, vol. 45, no. 6, pp. 1126-1136, 2022.

3D RADAR IMAGING FOR NON-COOPERATIVE TARGET RECOGNITION

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Abstract

This paper presents the ultimate results of the RING project. RING aimed to develop innovative solutions for Non-Cooperative Target Recognition (NCTR) using 3D Inverse Synthetic Aperture Radar (ISAR) imaging. Partners collaborated to design and prototype multi-band, multi-platform, and multi-static 3D Interferometric ISAR (InISAR) systems, advancing from low to mid-level Technology Readiness Levels (TRL 5/6) through field trials. Three trials in relevant scenarios validated both the 3D InISAR systems and NCTR algorithms, exceeding initial expectations. RING ended with a greater success than expected since the beginning. The successful implementation of the trials and the active involvement of both MoD during each phase of the project is testimony of the project success.

Keywords

ISTAR, multi-domain environment, multi-drones, 3D Interferometric-ISAR, NCTR

1. INTRODUCTION

NCTR relying on 2D ISAR images, has long been valued for target identification, yet it faces challenges due to its projection from a 3D domain onto a 2D Image Projection Plane (IPP). Unlike controlled optical imaging, ISAR projection introduces uncertainty due to target motion, complicating image interpretation and hindering accurate classification. Recent strides in addressing these challenges have led to the development of the 3-D InISAR technique, which bypasses IPP issues by creating a 3D reconstruction of the target. This breakthrough holds promise for revolutionizing NCTR methodologies by providing direct access to target 3D geometrical models, eliminating the need for angle variations or IPP projections adjustments, thus simplifying classification and reducing database requirements. Demonstrations have shown InISAR's potential in achieving accurate 3D reconstructions and enhancing system robustness across diverse target types and scenarios. However, realizing the full potential of 3D InISAR for NCTR requires further algorithm enhancements, necessitating real-world data investigation and the deployment of interferometric systems in operational settings. Answering this need, the 3D Radar Imaging for NCTR (RING) project has been initiated, partially funded by the Ministries of Defence (MoD) of Italy and Poland within the EDA framework. RING aims to advance and validate novel 3D InISAR-based NCTR algorithms through the development and deployment of three distinct interferometric radar system demonstrators, tailored to specific radar platforms. This approach includes a multi-band active ground-based system, a ship-borne

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system, and a drone-based system comprising a fleet of four drones flying in formation. RING's comprehensive strategy reflects its dedication to fostering innovation and operational readiness in NCTR technologies.

In [1] and [2], both the EDA and NATO S&T, identify Intelligence, Surveillance, Target Acquisition and Reconnaissance (ISTAR) information sources and AI, as critical to provide shared situational information and timely awareness and early warning in a multi-domain environment. RING partners have demonstrated that 3D InISAR combined with NCTR algorithms has significant potential to improve ISTAR capabilities. Furthermore, we explored a frugal and robust AI-based approach to mitigate the need for large training datasets and address trust-level errors, presenting promising ways to showcase these capabilities. However, the urgent need is now to bring this technology to maturity for seamless integration into current and future ISR systems. By doing so, we will be able to amplify operational capabilities and ensure lasting relevance in dynamic defence landscapes.

2. THE 3D ISAR IMAGING APPROACH

The 2D-ISAR image is a filtered projection of a 3D target's reflectivity onto the IPP, but unknown radar-target geometry complicates this. 3D InISAR is proposed to bypass these complications. The 3D InISAR uses interferometry and 2D ISAR images from different receivers to estimate scatterers' height. Unlike InSAR, which assumes target cooperation, joint estimation of scatterer height and ISAR IPP orientation is necessary in InISAR. The 3D InISAR approach utilizes a dual interferometric system with at least three receivers to create two orthogonal baselines.

2.1. GEOMETRY

Fig. 1 displays the antenna system and geometry, where Ω_{eff} represents the effective rotation vector of the target due to its movements that contributes to the synthetic aperture formation in the Coherent Processing Interval (CPI). The illustration in Fig. 1-(left) depicts a "canonical" geometry, where antennas lie on a 2D plane perpendicular to the radar Line of Sight (LoS). However, practical implementations may encounter challenges due to physical limitations, leading to a "squinted" target, as shown in Fig. 1-(right), where the LoS is rotated by angles α and β relative to the antenna plane. Though distances between antennas remain constant, their projections onto the perpendicular plane vary with α and β. Consequently, an equivalent antenna configuration, including dummy antennas positioned at these projections, must be considered. These "equivalent antennas" form "equivalent baselines," altering the antenna setup. While the core principles of the 3D InISAR algorithm remain relevant, adjustments for "equivalent baselines" rather than actual ones are necessary in such scenarios, [3][4][6].

2.2. ALGORITHM

The 3D InISAR algorithm comprises four key steps: 1) Multistatic 2D ISAR Formation to form 2D ISAR images at each receiver; 2) Coregistration to precise alignment the three 2D ISAR images both in amplitude and phase, 3) Scatterer Extraction to identify the most powerful scatterers that compose the 2D ISAR images, 4) 3D Target Reconstruction that utilizing information from scatterer extraction, estimates the scatterer height reconstructing the target's 3D ISAR image. where D_{tg} is the target size and R_0 is the average target to radar distance. This may limit the applicability of the system to specific scenarios and targets. As for example, tailored to the drone based system, for example, this constraint prevents arranging drones in a "canonical" geometry as shown in Fig. 1. Therefore, the formation must be carefully selected to satisfy baseline and minimum distance requirements for safe flight. However, ensuring unambiguous interferometric phase requires to suitably define baselines. Ambiguous interferometric phase can lead to uncertain scatterer heights. Avoiding this necessitates baseline lengths below a certain upper bound, [1][4], defined as follows:

$$d_{H/V} \le \lambda R_0/D_{tg}$$

The upper bound for baselines refers to the “effective” baseline, while minimum safety distance between drones refers to the Euclidean distance among drones.

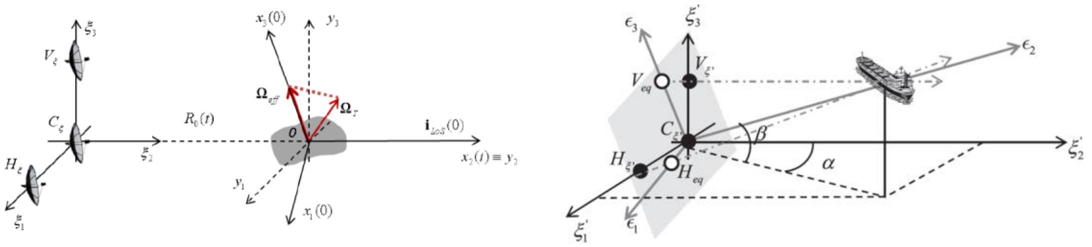

Figure 1: Canonical geometry (left) – non canonical geometry (right).

Hence, distance can ensure safety between drones without affecting required baselines for the 3D InISAR algorithm and drones can be therefore arranged as shown in Figure 2-(left).

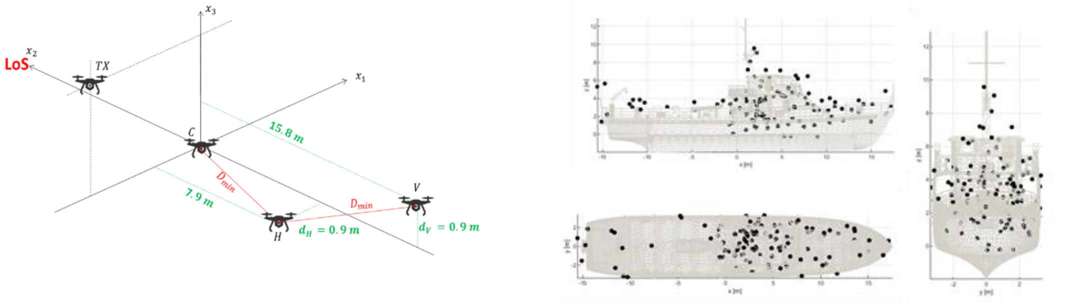

Figure 2: Example of the drones formation (left) – Example of 3D InISAR results (right). The 3D InISAR output (dark dots) has been superimposed to the target CAD model.

3. THE RING DEMONSTRATORS

Three 3D multistatic InISAR systems have been designed, realized and tested in scenarios of military relevance. The system have been implemented using Software Define Radar (SDR) architecture and COTS components. The ground-based system has been conceived for aerial scenarios and the targets were military aerial vehicles. The drone-based and the shipborne have been conceived for maritime scenario and the targets were small, medium and large ships.

3.1. GROUND-BASED INISAR SYSTEM

The ground based system is a dual-band interferometric radar operating simultaneously at C-band and X-band. Fig. 3 shows a picture of the ground based radar systems used during the trials that have been executed in Poland at the tactical air base in Malbork. Fig. 4 shows an example of 3D InISAR results. The system is composed of two transmitters and 4 receivers per band arranged in a way to form a rectangular, providing horizontal and vertical baselines. The C-band carrier frequency is 5.52 GHz and the instantaneous bandwidth is 500 MHz. The X-band carrier frequency is 9.6 GHz and the instantaneous bandwidth is 1 GHz.

3.2. SHIP-BORNE INISAR SYSTEM

The shipborne radar demonstrator is composed of three radars: an X-band monostatic active radar, able to transmit and receive pulsed NLFM (Non-Linear Frequency Modulated) waveforms, and two passive radars equipped with the same receiver chain of the monostatic radar. All radars have a rotating antenna. The three radars share the same Local Oscillator via a fiber optic link network, which guarantees phase synchronization. The transceiver performs standard surveillance and navigation tasks. When a target of interest is identified during ordinary surveillance mode, the radar system can be switched to imaging mode, so that all three radars point automatically to the target of interest: the monostatic radar illuminates the target, and all three radars receive echoes backscattered by the target. The antennas stare at the target of interest until the acquisition process, which is necessary for 3D ISAR imaging, is completed (about 1 second of duration).

Figure 3: Dual-band ground based radar (left) – trials site (right)

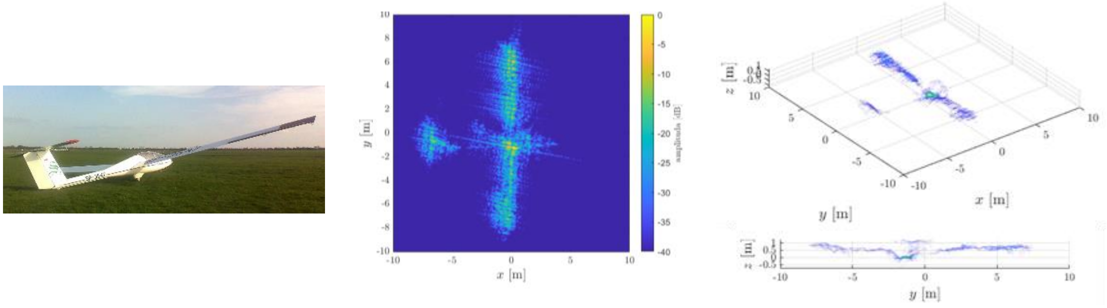

Figure 4: Dual-band ground based radar results. From left to right: target, 2D-ISAR, 3D-InISAR

When operating in surveillance mode, the transmitter' antenna rotates and transmits a pulse with instantaneous bandwidth $20MHz$. When operating in the imaging mode all the three antennas point towards the target of interest, a range gating is applied to focus on the target, the PRF increases to transmit a stepped frequency (SF) waveform designed to provide an instantaneous bandwidth equal to $300MHz$ and to avoid ambiguities in the ISAR image. The radar shifts seamlessly between surveillance and imaging modes for selected targets, requiring dynamic adjustment of waveform parameters and antenna rotation. During the trials, the radar system was installed on the roof of the Vallauri building, as shown in Fig. 5. Although this installation is on a fixed structure and not on board a ship, it emulates realistically a hypothetical ship-borne geometry in terms of antenna physical distances and baseline non-orthogonality. Fig. 5-(right) shows a picture of the geometry of data acquisition. The targets' path, approaching or leaving the Livorno harbor are represented in dark dashed line.

3.3. DRONE BASED INISAR SYSTEM

The system consists of a multistatic radar network, one radar node is transmitting and three radar nodes are receiving. Each radar node is carried by a flying drone. The radar waveform is transmitted by the Tx node and the echoes backscattered by the target are received simultaneously by the three Rx nodes. In particular, the radar front-end allows for the transmission of a Linear Frequency Modulated Continuous Waveform (LFMCW) signal, with a bandwidth of 600 MHz, around the 9.6 GHz carrier frequency. Ground Control Station (GCS) controls and configures drones, with telemetry parameters sampled by Real Time Kinematic (RTK) GPS receiver for accurate autopilot module use. Radar payload, developed by ECHOES, mainly composed of: 1) Digital control board which hosts the System on a Module (SoM), the SSD, the DAC and ADC converters and the input/output controller, 2) Power Management Unit (PMU) which manages all the power supplies needed by the radar sub-modules, 3) GPS Disciplined Oscillator (GPSDO) which is synchronized with the pulse-per-second (PPS) reference of the GPS for time and phase synchronization of the multistatic coherent radar network, 4) 4G router to remotely control the sensor.

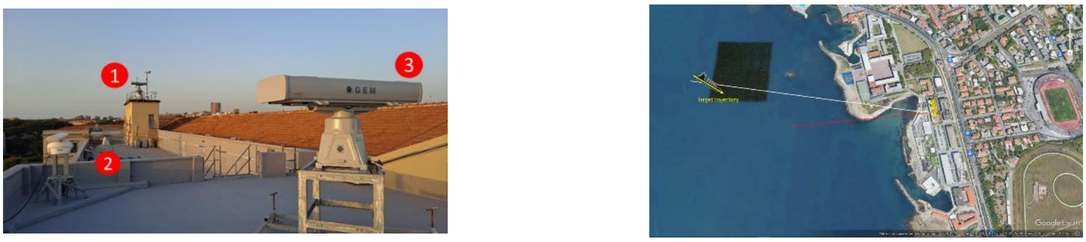

Figure 5: Shipborne radar (left) – trials geometry (right). The yellow line represents the radar LoS during the acquisition whose results are shown in Fig. 6 The target range was 19NM.

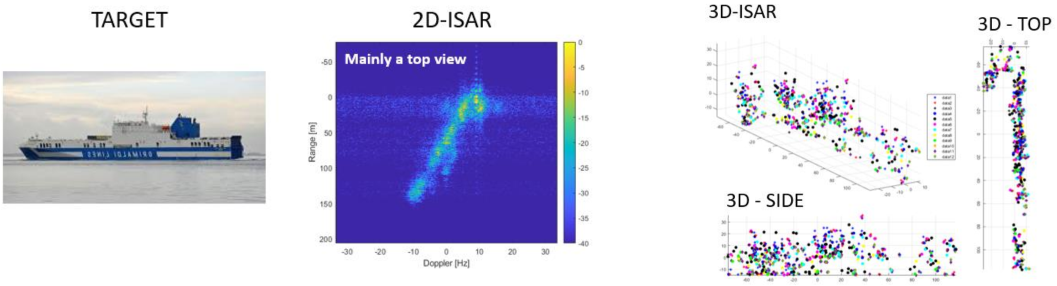

Figure 6: Shipborne radar results. From left to right: target, 2D-ISAR image and 3D-InISAR. Different colors refer to different CPIs.

Drones are unmanned multicopters with maximum take-off weight of 20 kg. Details can be found in [6][7]. Fig. 7-(left) shows the drones during a trials session looking at the target that was at a distance of 700m from the radar, (yellow lines in Fig. 5-(right)).

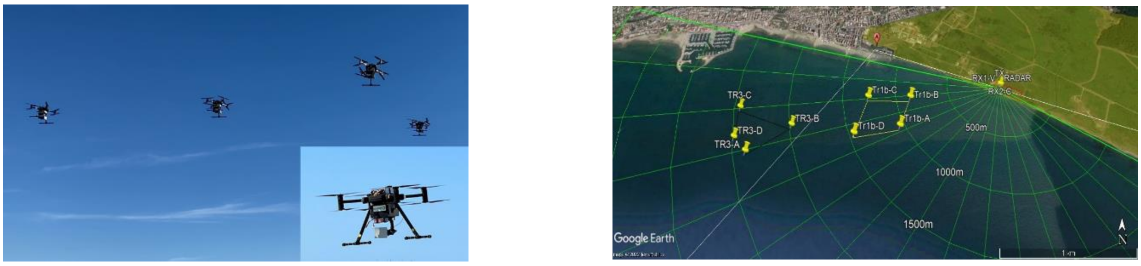

Figure 7: drone based radar (left) – trials geometry (right)

4. THE RING ACHIEVEMENTS

Simultaneously with the development of multistatic 3D InISAR systems and trials execution, the partners have designed algorithms to boost the robustness and reliability of the 3D InISAR technique and have devised new NCTR algorithms that exploit 3D ISAR images. Few articles cover this topic due to the early stage of 3D InISAR, with limited attempts as in [8].

4.1. 3D INISAR RESULTS

Fig. 8 shows example of the 3D InISAR results obtained by processing data acquired by the drone based system. Fig. 9 shows example of the 3D InISAR results obtained by processing data acquired by the X-band ground based system.

4.2. 3D NCTR RESULTS

To deeply investigate this topic, RING partners have ideate, implemented and validated three different algorithms: 1) a CAD model based ATR algorithm, 2) a silhouette based ATR algorithm, 3) a Deep Learning (DL) based ATR algorithm.

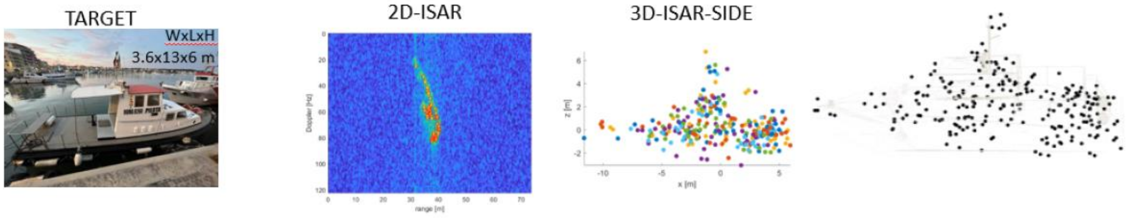

Figure 8: drone based radar results from left to right: target, 2D ISAR image, 3D InISAR, superposition of the 3D InISAR to the CAD model, [7].

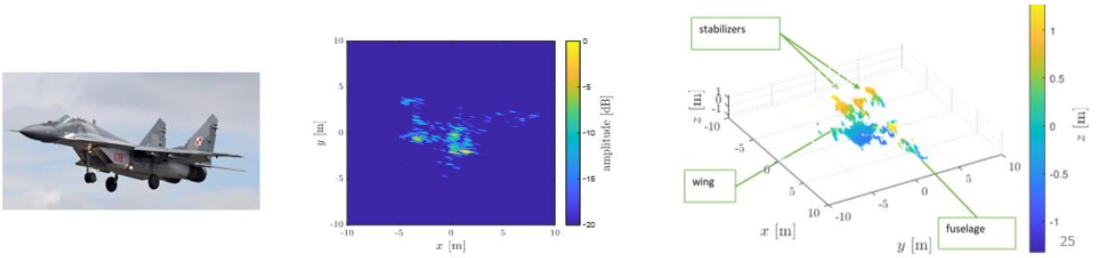

Figure 9: ground-based radar results from left to right: target, 2D ISAR image, 3D InISAR.

4.2.1. MODEL BASED NCTR ALGORITHM

The model based algorithm implements a two-stage approach: firstly it discriminates among small, medium-size and large targets, secondly it implements target recognition by making use of a set of 3D geometrical CAD models of targets. This comparison is carried by utilizing similarity indexes and a global score to gauge the overall resemblance between the CAD model and the 3D ISAR image. This can be done however after a proper alignment approach aiming at automatically finds the best alignment between the 3D ISAR image and each CAD model. The alignment process consists of two steps, employing both Principal Component Analysis (PCA) and the Iterative Closest Point (ICP) method. A results is illustrated in Fig. 2-(right) where the 3D cloud of points has been aligned with the CAD model of the target. The similarity index, measures the similarity, and the target class is the one with the highest similarity degree among all the classes.

4.2.2. SILHOUETTE BASED NCTR ALGORITHM

As the CAD model-based, this classifier implements a two stage approach, but it differs mainly in the second stage, since target recognition is conducted by comparing the shape of the 3D ISAR image with a 2D shape of the target. The full description of the algorithm is reported in [5]. A similar alignment algorithm based on PCA and ICP is performed to align the reference 2D silhouette of each target with the 3D ISAR image projected onto the same 2D plane. Subsequently, the algorithm employs a color-coding image to visualise the results, enhancing the user's comprehension of the results. This visualization is then transformed into six numerical indices, which the algorithm ultimately utilizes to make decisions. The visual tool allows any operator to immediately understand the quality of the results, allowing the operator to intuitively and easily judge the reliability of the decision inferred by the classifier. Fig. 10 shows example of the colour coding visualization before classification. In this case the reconstructions formed by the cloud of points have been superimposed to the silhouette of two targets. Specifically, these reconstruction have been obtained by processing the shipborne data and refer to the Amerigo Vespucci (AV) and the a general cargo vessel (CV). The first row represents the 3D ISAR of the AV target compared with the silhouette of both AV and CV. The second row shows instead the 3D ISAR of the CV compared with the silhouette of both AV and CV. In both cases the classifier takes the correct decisions.

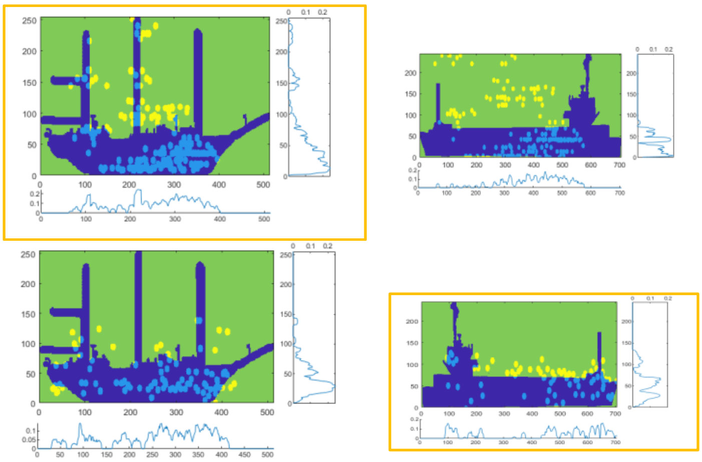

Figure 10: Example of the results of the silhouette base NCTR algorithm, obtained by processing shipborne data.

4.2.3. DL BASED NCTR ALGORITHM

Extensive research on DL-based NCTR has been conducted to design the classifier, with the aim to reduce the need for large training data while addressing trust level errors. With these two objectives in mind, a two-stage classification approach was implemented. The first stage determines the validity of ISAR images for classification, requesting new data if necessary, while the second stage performs the actual target classification. A Convolutional Neural Network (CNN) was optimized for pre-classification purposes to measure the quality of the input image. To accomplish classification by however limiting the size of the necessary training set, both classification stages were trained on simulation data, followed by transfer learning (TL) using a subset of the acquired data. Further, a pre-processing step simplified input data, reducing the complexity of the CNN architecture. TL leverages knowledge of the simulation data to classify the measurement data, and the weights of the dense layers of the pre-trained models are adjusted based on the measurement data. The overall dataset is composed of 540 3D ISAR images and after a training from scratch using simulated data, TL and fine tuning have been applied using 431 samples, while 109 are used for validation. Fig. 11 shows the overall block diagram of the DL-based ATR algorithm and the classification results by means of the confusion matrix.

4.2.4. OVERALL NCTR RESULTS

The trials produced two primary datasets of 3D ISAR images. The first dataset included 4 aerial targets, yielding nearly 540 3D ISAR images. The second dataset consisted of 6 ships (2 small, 2 medium-sized, and 2 large ships), resulting in nearly 100 3D ISAR reconstructions. The CNN was evaluated using the aerial dataset, while the shipborne and drone-based systems were assessed using maritime targets. Since they do not require training, there are no strict dataset requirements for either. The overall accuracy performance tested on real data acquired during the RING project are summarized in the table below.

5. CONCLUSIONS

This paper presents an innovative solution that leverages 3D ISAR imaging to overcome the limitations of conventional 2D ISAR systems. Through the development and validation of three distinct demonstrators, ranging from land-based, naval-based and drone-based platforms, we have demonstrated the effectiveness of our innovative approach in various scenarios.

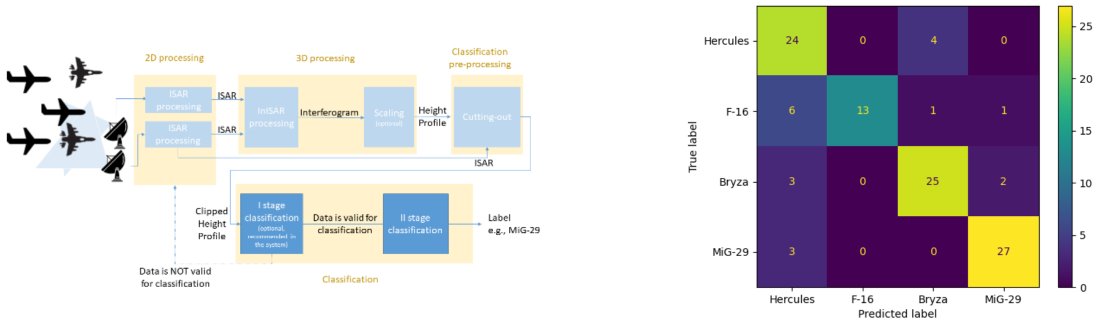

Figure 11: DL-based NCTR block diagram (left) and confusion matrix (right)

Table 1: comparison of the NCTR algorithm in terms of overall accuracy measured on real data

Demonstrator	Algorithm	Accuracy of the classification
ship-borne radar demonstrator	Database free	87.5% (medium-size ships)
		91.6% (large ships)
	CAD model-based	60.7% (medium-size ships)
		66.4% (large ships)
ground-based X-band active radar demonstrator	Deep learning-based	81,65%
Flying drone radar demonstrator	Database free	83.3% (small ships)
	CAD model-based	81.6% (small ships)

The journey from conceptualization to realization has been marked by significant innovations, culminating in successful field trials that have pushed our technology from the early stages of low TRL to TRL 5/6. Despite the challenges encountered, particularly in the field of drone systems, the determination of our consortium ensured the successful development of the project. The active involvement of both MoDs throughout the project underlines its success and the considerable interest it has aroused among end-users. However, to fully integrate this technology into existing and future ISR systems, further advancement towards maturity is essential, which promises improved operational capabilities in evolving defence environments. The successful implementation of the demonstrator also generated valuable data for future research, potentially laying the foundation for future iterations of the RING project.

References

[1] EDA – The EU Capability Development Priorities https://eda.europa.eu/docs/default-source/brochures/qu-03-23-421-en-n-web.pdf.

[2] NATO Science & Technology trends 2023-2043, https://cesmar.it/wp-content/uploads/2023/04/stt23-vol1.pdf

[3] M. Martorella, D. Stagliano, F. Salvetti and N. Battisti, "3D interferometric ISAR imaging of noncooperative targets," in IEEE Transactions on Aerospace and Electronic Systems, vol. 50, no. 4.

[4] F. Berizzi, M: Martorella, E. Giusti, “Radar Imaging for Maritime Observation”, CRC Press, 2018

[5] S. Ghio, E. Giusti and M. Martorella, "Low-cost database-free automatic target classification using 3D-ISAR," 2022 23rd International Radar Symposium (IRS), Gdansk, Poland, 2022, pp. 178-183

[6] E. Giusti, S. Ghio and M. Martorella, "Drone-based 3D interferometric ISAR Imaging," 2021 IEEE Radar Conference (RadarConf21), Atlanta, GA, USA, 2021

[7] E. Giusti, S. Ghio and M. Martorella, "Drone-based 3DInISAR: Experimental Results," 2023 IEEE Radar Conference (RadarConf23), San Antonio, TX, USA, 2023.

[8] J. Cai, M. Martorella, Q. Liu, E. Giusti and Z. Ding, "The alignment problem for 3D ISAR imaging with real data," EUSAR 2021; 13th European Conference on Synthetic Aperture Radar, online, 2021.

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SPINAR: SPIN-BASED ARTIFICIAL NEURAL NETWORK FOR EMBEDDED RF PROCESSING

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Abstract

Classification of RF signals is key to many defence applications, such as electronic warfare. Artificial neural networks have recently proven competitive to perform RF signal classification. However, running such algorithms relies on digitization and digital AI hardware (GPUs, FPGAs, ASICs), which size, power and energy consumption limit their deployment on embedded systems. This issue is exacerbated for wideband inputs. SPINAR proposes to implement neural network directly in hardware with spin-based nanoscale devices. Such devices can perform classification of analogue RF inputs without digitization over the 50 MHz to 50 GHz band in parallel, at high speed (microsecond) and low energy cost (nano Joules), within a single microelectronics chip compatible with existing systems. Recently, we have achieved a small-scale experimental proof of concept. In this study, we use numerical simulations to demonstrate that our system can perform an electronic warfare inspired task and show its advantages compared to conventional methods.

Keywords

Nanotechnology, Radiofrequency, Artificial Intelligence, Neural Networks, Electronic Warfare

1. INTRODUCTION

Defence applications such as radar detection and electronic warfare rely heavily on the classification of radio-frequency (RF) signals. In order to respond to potential threats, classification has to be performed very quickly and encompass the whole Radio Spectrum (typ. 0 - 50 GHz). In order to be deployed to all armed forces, including for embedded systems, classification has to be frugal in cost, size, weight, power and energy consumption. An extremely promising way to analyze RF signals is to use artificial intelligence. Neural networks have proven to be more accurate and more resilient to real-world conditions (noisy electromagnetic environment, imperfect RF components or antennas etc.) than conventional algorithms which rely on specific features extractors and complex analysis tools [1].

Currently, applying artificial neural networks to RF signals requires to first digitize the signal sensed by the antenna and then to use and run a neural network on conventional CMOS-based hardware (such as a CPU, GPU, FPGA or ASIC). Figure 33 depicts this process for the example of emitted type identification. Both stages of the process are computationally heavy, leading to delays (a few miliseconds) and high power and energy consumption (hundreds of Watts) [2].

We propose a radically new way to process RF signals. A neural network implemented directly in hardware with RF spin-based nanodevices behaving as neurons and synapses will process raw RF analogue signals immediately after the antenna. This solution bypasses digitization and provides massive gains: large instantaneous bandwidth (50 MHz – 50 GHz), small size (mm2 chip), high speed (µs per computation), low power consumption (1W) and 100-fold improvement in energy efficiency.

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Recently, within the EU PADR project SPINAR, we have achieved a first experimental demonstration of classification of analogue RF signals by a hardware neural network of spin-based nanodevices [3]. Furthermore, we have experimentally demonstrated how to cascade layers of spin-based neurons and synapses, a critical step towards deep neural networks [4]. In this paper, we present for the first time our full concept and how it applies to defence. Furthermore, we perform numerical simulations of a spin-based neural network hundreds of times larger than what current experiments. We demonstrate an RF signal classification task inspired from electronic warfare. Finally, we benchmark our system and demonstrate a competitive advantage against current methods.

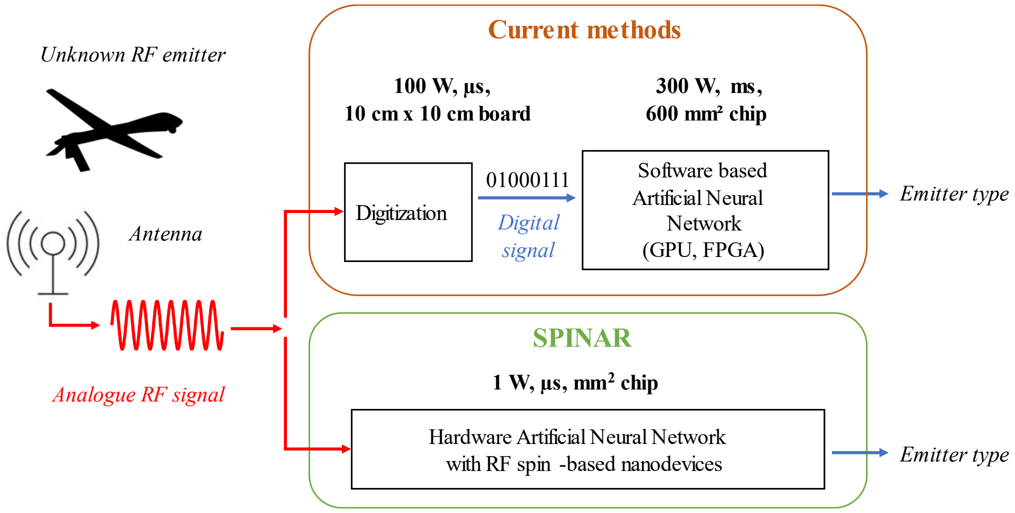

Figure 33. Implementation of SPINAR enabled technology in future defence systems, vs current methods.

2. THE SPINAR CONCEPT

2.1. MASSIVE INSTANTANEOUS BAND FROM 50 MHZ TO 50 GHZ

Conventional digitization equipment requires several channels to cover a broad frequency range, each channel covering about 150 MHz, consuming about 10 W and costing about a thousand euros [2]. State-of-the-art equipment to reach the highest frequencies is subject to sovereignty issues. We propose to remove digitization altogether. SPINAR relies on spin-based nanodevices, called magnetic tunnel junctions, depicted in Figure 34(a). These ferromagnetic pillars can be fabricated down to a few nanometres and monolithically integrated on CMOS in standard foundry process. They exhibit high-speed dynamics [3, 4]. The magnetization of the top layer can oscillate in response to radiofrequency currents, generating a DC voltage across the device, as shown in Figure 34(b). We can modify the resonant frequency of the device through its size, geometry, or by application of voltage pulses [5], covering the 50 MHz to 50 GHz range [6]. The response amplitude is proportional to the received RF power, performing a rough Fourier-like coefficient extraction [7]. An array of spin-based devices can process the whole 50 MHz to 50 GHz range in parallel, in less than a micro-second.

2.2. ENERGY-EFFICIENT HARDWARE NEURAL NETWORK

Running neural networks on conventional CMOS processors is energy costly, which limits the complexity of artificial intelligence tasks that can be performed by embedded systems [8]. Our vision is to implement a neural network directly in hardware, as shown in Figure 34(c-d). We have experimentally demonstrated that the spin-based nanodevices can implement artificial neurons (non-linear activation functions) [9], as well as synapses (tunable weighted sums) [3]. We have experimentally demonstrated that we can connect the neurons and synapses into networks and perform classification of analogue RF signals [3, 4]. As shown in Figure 34(d), the first layer of the network performs wideband Fourier-like extraction and the next layers perform neural network operations on the coefficients, outputting the class of the signal (for instance the emitter type). In our patented architecture [10], the memory -- implemented by the non-volatile behaviour of the spin-based synapses -- is intertwined with the computing. This greatly limits the need for access to external memory, which is responsible for most of the cost of neural networks in terms of time and energy.

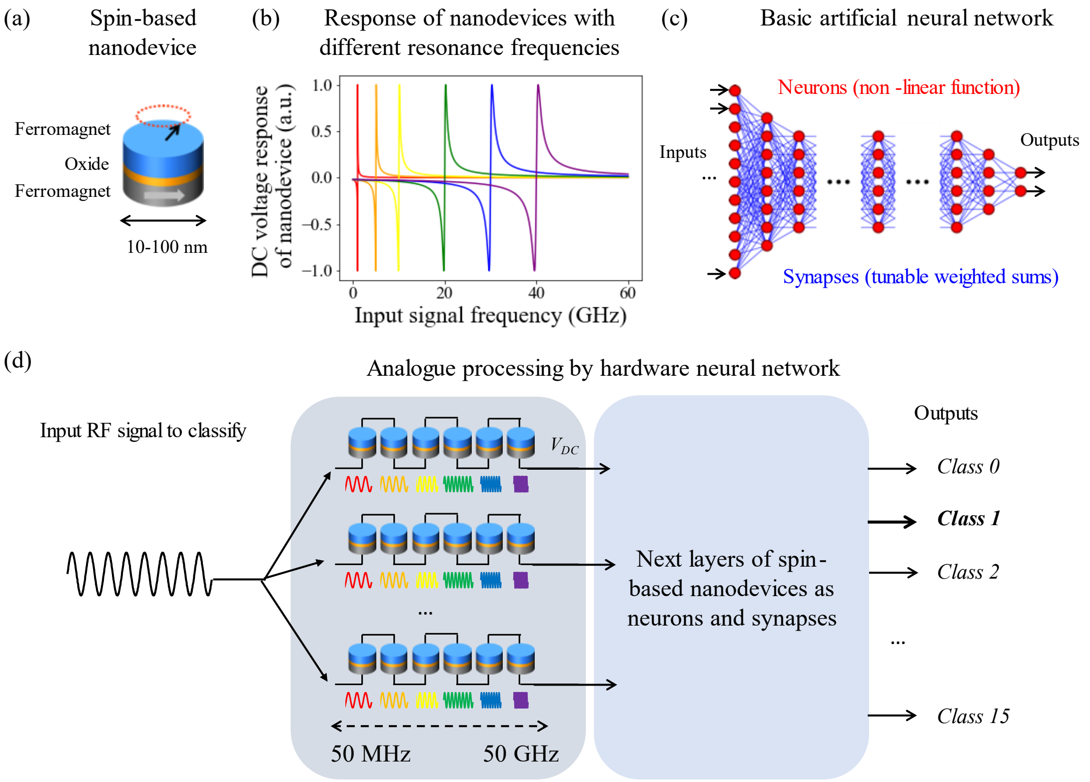

Figure 34. (a) Schematic of a spin-based nanodevice. The magnetization of the top layer is free to rotate while the bottom layer's is fixed. (b) DC voltage response of a nanodevice to an RF signal, versus the input frequency. Each colour corresponds to a device of different resonance frequency. (c) Schematic a basic artificial neural network, with neurons (red) performing non-linear activation functions, connected by synapses (blue) performing tunable weighted sums. (d) Analogue processing by the hardware neural network: a first layer of nanodevices performs a wideband rough extraction of Fourier coefficients on the input RF signal. The next layers of nanodevices perform non-linear functions and weighted sums, to output the predicated emitter class.

3. RF SIGNAL CLASSIFICATION

Our first experimental demonstrations of spin-based neural network and RF signal classification were a key proof of concept, but are limited today to less than ten devices and thus tackled a toy task. In order to prepare the scaling up of our system, we have developed a simulator of the spin-based neural network (described in Section 3.2), which relies on experimentally verified models and which we use to perform an electronic warfare inspired task.

3.1. ELECTRONIC WARFARE INSPIRED TASK

We design a dataset and classification task, inspired from emitter type identification. Our dataset has 15 classes of RF signals. Different classes have different frequency ranges, which partially overlap, corresponding to groups of applications, as described in Table 4. In a real-life use case, each class could correspond to an emitter type, to be recognized by the network. Within each class there are 200 signals (100 for training and 100 for validation) which are power density spectra, each exhibiting random variations (frequencies, mean power and spectrum shape). Each spectrum is encoded with frequency sampling bins of 4 MHz from 0 to 40 GHz, i.e. a vector of 10,000 elements. Figure 35 shows three examples of signals, represented as images. This task is simple and meant as a first demonstration.

Table 4. Dataset

Application group	Class in group	Target class	Frequency range (GHz)
Group 1: “UHF” Very long-range radars, ballistic missiles detection	Class 1	0	0.35 - 0.6
	Class 2	1	0.55 - 0.65
	Class 3	2	0.7 - 0.8
	Class 4	3	0.9 - 1
	Class 5	4	0.95 - 0.98
Group 2: “C-band” Short-medium range surveillance radars for weapons systems	Class 1	5	4 - 4.5
	Class 2	6	4.4 - 4.7
	Class 3	7	4.5 – 4.6
	Class 4	8	4.8 - 5.3
	Class 5	9	5.6 - 6.1
Group 3: “K-bands” High resolution cartography, satellite altimetry and communication, maritime navigation	Class 1	10	12.3 - 12.8
	Class 2	11	12.7 - 13.1
	Class 3	12	12.9 - 13.3
	Class 4	13	15 - 15.5
	Class 5	14	15.2 – 15.4

Figure 35. Examples of signal spectra for three classes (resp. 1, 8 and 15). Each spectrum is represented as an image, where each pixel (indexed by rows then columns) represents a frequency bin of 4 MHz and its intensity is the power density.

3.2. NEURAL NETWORK SIMULATOR

The neural network simulator uses the open machine learning library PyTorch, as well as physical models of the RF dynamics of the spin-based nanodevices. These models were developed and validated by comparison to experiments [3, 4]. In this work, we focus on simple feed-forward fully connected architectures, as shown in Figure 34(c). However, the building blocks depicted here can be applied to more complex architectures such as convolutional neural networks and transformers.

3.2.1. SPIN-BASED DEVICES AS SYNAPSES

The spin-based devices are chained in series, as shown in Figure 34(d). Each chain generates a DC voltage which corresponds to a weighted sum of the Fourier coefficients of the input signal:

$$V_j = \sum_i P_i W_{ij} \, .$$

Where Vj is the voltage across the chain j and Pi is the power density of input frequency f_i^{inp} (sampling bin i). Each weight W_{ji} is controlled by the resonant responses $G_{jik}$of the spin-based synapses, which can be positive and negative, as shown in Figure 34(c):

$$W_{ji} = \sum_k G_{jik} \text{ with } G_{jik} = \frac{2\alpha f_{jk}^{\mathrm{res}}\left(f_i^{\mathrm{inp}} - f_{jk}^{\mathrm{res}}\right)K_{SD}}{\left(\alpha f_{jk}^{\mathrm{res}}\right)^2 + \left(f_i^{\mathrm{inp}} - f_{jk}^{\mathrm{res}}\right)^2}$$

Here $\alpha = 0.01$ (Gilbert damping) and $K_{SD} = 8.8 \times 10^3\ \mu\mathrm{V}/\mu\mathrm{W}$ (spin-diode sensitivity) are device parameters. Each device receives the whole input frequency range, but its response is small for frequencies far from its resonance. Each weight W_{ji} involves the resonance frequencies of all devices in the chain. In consequence, the trainable parameters of the network are the resonance frequencies f_{jk}^{res} (rather than the weights directly, as is the case in a standard network).

A trainable bias is added to each voltage V_j, as in standard neural networks. We learn the frequencies and biases using the PyTorch automatic differentiation tools as well the ADAM gradient descent optimizer.

3.2.2. ACTIVATION FUNCTION AND FULL NETWORK

When a DC current is injected into a spin-based device, its top magnetization can exhibit high-speed oscillations, giving rise to an RF voltage. The emitted RF power is a non-linear function of the input DC current. This function is similar to the ReLU (Rectified Linear Unit) activation function, with a non-zero threshold (minimum current required to sustain the oscillations) and a slope depending on material parameters [3, 4, 9].

The spin-based neurons take as inputs the DC signals of the synaptic chains, and output RF signals which can then be fed to the synaptic chains of the next layer. Transconductance DC amplifiers and transimpedance RF amplifiers are required before and after the neurons respectively. The exact amplification values are hyperparameters, optimized along the learning rate, using the Optuna library. The RF-to-DC and DC-to-RF conversions at each layer makes the architecture modular and scalable to deep networks.

3.3. SIMULATION RESULTS

We start by training a spin-based single layer perceptron on the dataset, both because this is the simplest architecture and because our focus is the first synaptic layer which directly tackles the analogue RF input signal. The synaptic layer is an array of 15 chains, for the 15 classes. Figure 36(a) shows the evolution of the accuracy (i.e. proportion of correctly classified signals) versus the number of epochs. We reach 99.50 % accuracy (± 0.12 % of standard deviation over 50 trials) on the validation dataset. Figure 36(b) shows the corresponding confusion matrix. Here, the number of devices per chain is 512. By adding a second synaptic layer and 128 hidden neurons, we reach an accuracy of 99.91 ± 0.08 %.

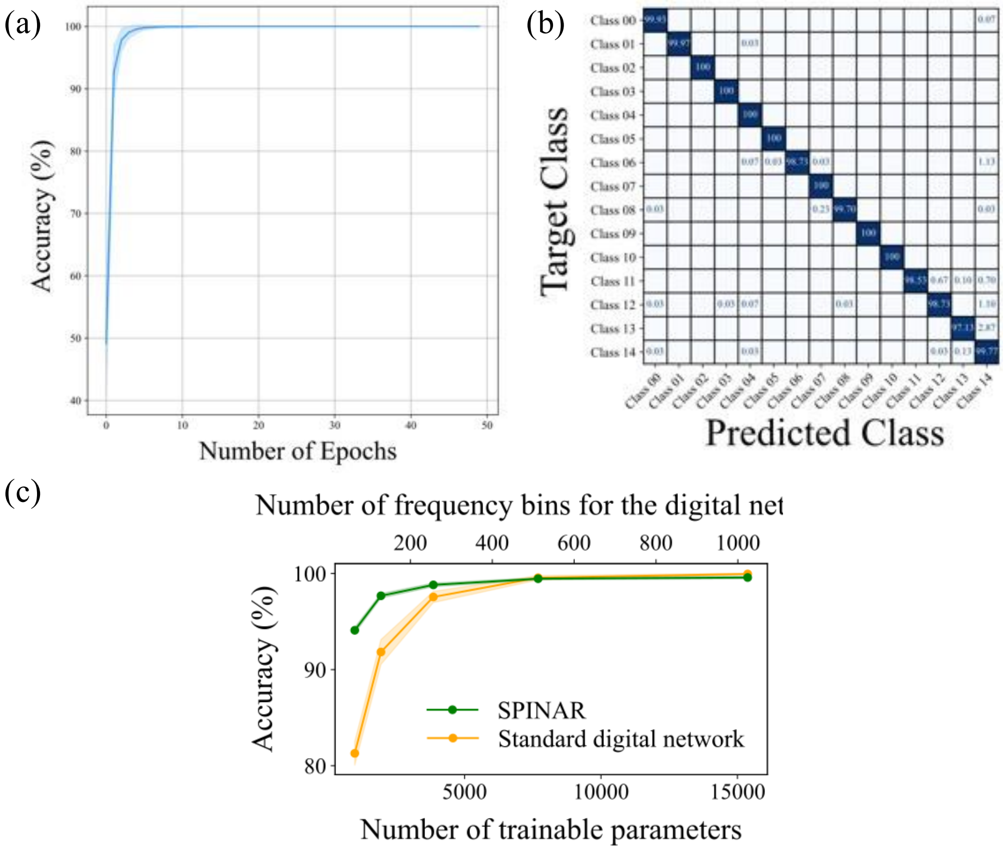

Figure 36. (a) Accuracy (percentage of correctly classified signals) versus the number of epochs (i.e. whole training dataset). (b) Confusion matrix on the test dataset. (c) Accuracy versus the number of trainable parameters, for the standard digital (orange) and spin-based (green) networks. For the digital network, the number of parameters is linked to the number of frequency bins of the input. In (a) and (c), the solid lines are mean values and the coloured zones represent the standard deviation over 50 trials.

The green curve in Figure 36(c) shows how the accuracy of the spin-based single-layer perceptron depends on the number of trainable parameters, i.e. the frequencies of spin-based synapses and the biases. Chains with 64,128, 256, 512 and 1024 devices each give rise to networks with 975, 1935, 3855, 7695 and 15375 trainable parameters respectively. We observe that the accuracy decreases when the number of parameters is too low. Indeed, the network loses computational power. Furthermore, the spin-based devices become too sparsely spread across the frequency range: the response of network to some parts of the spectrum is not high enough.

We now compare our system to a standard digital single-layer perceptron. Here, the synaptic layer performs weighted sum on the inputs. The size of the input dictates the number of weights in each weighted sum, and thus the number of trainable parameters. The size of the input is the number of frequency bins in the spectra. In consequence, reducing the number of trainable parameters requires to reduce the sampling of the input spectrum. This is a critical difference with the spin-based perceptron, where the input is analogue. While our numerical simulation is obviously digital, the number of trainable parameters does not depend on the sampling of the input. The orange curve in Figure 36(c) shows how the accuracy of a standard digital single-layer perceptron depends on the number of trainable parameters, which derive from the number of frequency bins of the input. We observe that the spin-based neural network is more resilient than the standard digital network to reducing the number of trainable parameters. This is because the spin-based network processes the analogue signal over the whole spectrum, independently of the number of trainable parameters.

Reducing the number of trainable parameters directly results in reducing the footprint and energy consumption of the system. In consequence having a hardware spin-based neural network compared to a standard digital implementation can improve the computing capacity when the size and energy constraints are important.

4. BENCHMARKING

In order to estimate the energy consumption of the spin-based system, we take into account the full architecture, including the amplifiers [4]. We estimate that the power consumption is about 10-7 W per synapses and 10-6 W per neurons. Furthermore, our system is as fast as the response of the spin-based devices, classifying signals in less than a microsecond. The energy consumption of the system is about 10 fJ per synaptic operation and 100 fJ per neuronal operation, resulting in an efficiency of 100 Tops/W. Overall, the consumption is below 100 pJ per signal classification. The network to perform the task shown here would consume about 1 mW and 100 pJ. A budget of 1 W of could power a chip with millions of components and thus perform more complex tasks.

In contrast, conventional systems (FPGAs, ASICs or GPUs) consume more power and energy. Running networks roughly the same size as ours to classify the benchmark task MNIST consumes from microJ to mJ per image on digital hardware [11]. This is orders of magnitude higher than the spin-based network. Furthermore, when tackling RF inputs, the digitization itself is costly. The RF signal can be either acquired by devices such as a Universal Software Radio Peripheral, which are bulky and consume tens of Watts, or directly on chip, which requires integrated Analogue to Digital Converters. A single state of the art high speed ADC designed specifically for low power consumption consumes several mW [12], more than our complete system for the simple task shown here. Furthermore, these ADCs are not wide frequency band, so several would need to be used to cover the whole spectrum in parallel as done by the spin-based network.

5. CONCLUSIONS

SPINAR proposes a radically new way to perform artificial intelligence on RF signals. Our vision is to build a hardware neural network using spin-based nanodevices as neurons and synapses. Due to their high-speed dynamics, these devices can perform Fourier-like extraction on analogue RF signals, over a wide frequency range (50 MHz – 50 GHz) in parallel. Recently, we have achieved a small-scale experimental proof of concept of our system. In this study we have demonstrated by numerical simulations that a spin-based neural network can classify RF signals from a database inspired from Electronic Warfare. In future works, we will tackle more complex network architectures and tasks.

The key advantages of our system are:

- No need for digitization or any type of pre-processing of the RF inputs.
- Processing in parallel of a large (50 MHz – 50 GHz) frequency range.
- Classification at high speed (below the microsecond), low power (1W for millions of devices) and low-energy consumption (below nano-Joules), orders of magnitude better than current technologies.
- Higher resilience to reduction of the number of trainable parameters.

Importantly, spin-based devices are extremely similar to the unit cells of Magnetic Random-Access Memories (MRAMs), which can be monolithically integrated by billions into conventional CMOS microelectronic chips and are already commercial products [13, 14]. We thus envision large and deep spin-based neural networks, capable of processing analogue RF signals over a wide frequency band, integrated with standard CMOS on a small chip, consuming little energy enough to be suitable for embedded systems. The tunability of the spin-based devices opens the way to on-chip reconfigurability and learning, so that the system can adapt to new conditions and uses during its life-time.

6. ACKNOWLEDGEMENTS

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References

[1] OShea et al. 2018. IEEE Journal of Selected Topics in Signal Processing, 12(1):168-79.

[2] The numbers provided for the digitization of RF signals in defence equipment provide both from internal discussions with Thales relevant Global Business Units and from external sources, such as “Military A/D and D/A converters come to grips with a complex, network centric world”, published in Military & Aerospace Electronics (https://www.militaryaerospace.com/computers/article/16721624/military-ad-and-da-converters-come-to-grips-with-a-complex-network-centric-world)

[3] Leroux, Nathan, et al. "Classification of multi-frequency RF signals by extreme learning, using magnetic tunnel junctions as neurons and synapses." APL Machine Learning 1.3 (2023).

[4] Ross, Andrew, et al. "Multilayer spintronic neural networks with radiofrequency connections." Nature Nanotechnology 18.11 (2023): 1273-1280.

[5] Choi, Jong-Guk, et al. "Voltage-driven gigahertz frequency tuning of spin Hall nano-oscillators." Nature communications 13.1 (2022): 3783.

[6] S. Bonetti et al, “Spin torque oscillator frequency versus magnetic field angle: The prospect of operation beyond 65 GHz”, Appl. Phys. Lett., 94, 102507 (2009)

[7] Kermorvant et al, "Analog spectrum analyzer" U.S. Patent 10,408,867, issued September 10, 2019.

[8] E. Garcia-Martin et al, “Estimation of energy consumption in machine learning”, Journal of Parallel and Distributed Computing 134 (2019) 75–88

[9] Torrejon, Jacob, et al. "Neuromorphic computing with nanoscale spintronic oscillators." Nature 547.7664 (2017): 428-431.

[10] Grollier, Julie. "Neural network comprising spintronic resonators." U.S. Patent Application No. 17/263,093., and French patent FR 18 00 805-7.
[11] Göltz, J., Kriener, L., Baumbach, A. et al. Fast and energy-efficient neuromorphic deep learning with first-spike times. Nat Mach Intell 3, 823–835 (2021).
[12] Liu, J., Hassanpourghadi, M. & Chen, M. S.-W. A 10GS/s 8b 25fJ/c-s 2850um2 Two-Step Time-Domain ADC Using Delay-Tracking Pipelined-SAR TDC with 500fs Time Step in 14nm CMOS Technology. in 2022 IEEE International Solid- State Circuits Conference (ISSCC) vol. 65 160–162 (2022)
[13] O. Golonzka, et al, "MRAM as Embedded Non-Volatile Memory Solution for 22FFL FinFET Technology", IEDM Tech. Dig. 2018.
[14] MRAM 16Mbit chips (i.e. comprising 16 million Magnetic Tunnel Junctions) are sold for less than 50 € (for instance on retailer https://www.arrow.com/en/categories/memory/memory-chips/mram)

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ARE THE EUROPEAN CHIPS ACT, CRITICAL RAW MATERIALS ACT, ECONOMIC SECURITY STRATEGY, AND GLOBAL GATEWAY NOT ENOUGH? – EU DEFENCE SECTOR CRITICAL RAW MATERIAL SUPPLY CHAIN VULNERABILITY SOLUTIONS FROM JAPAN

D. Seiler[1]

Abstract

The EU defence industry depends one-sidedly on China for critical raw materials required for high-tech weapons systems. After years of China's increasing geopolitical assertiveness and the implementation of coercive measures against EU member states, supply chains and thus future defence capabilities are under threat. EU countermeasures such as the European Chips Act, the Critical Raw Materials Act, the Economic Security Strategy and Global Gateway are far from sufficient to reduce dependencies on China in the defence supply chain. As a result, the EU's precarious dependency will continue for at least 15 years due to the long lead times for independent critical raw material supply chains. A role model for the EU to emulate must be Japan, which was forced to make geopolitical concessions to China following economic blackmail due to its one-sided dependence on critical raw materials, but then launched an extraordinary and high-cost, but also successful derisking strategy.

Keywords

Supply chain risks, critical raw materials, defence industry, EU-China relations, strategic autonomy

1. INTRODUCTION

“The Middle East has oil. China has rare earth metals” (Cohen 2023).

Chinese head of state Deng Xiaoping famously made this statement in 1992 in the light of the fact that the economic and political security of countries in the 20th century depended to a large extent on their access to oil (Cohen 2023). Nowadays, the European Union (EU) is confronted with an immense dependency towards China in terms of critical raw materials (CRMs) such as rare earth metals and processed products such as semiconductors and alloys (European Commission 2020: 10-15). The existing supply chain risks particularly affect the defence industry, where these raw materials are unsubstitutable due to their specific characteristics.

The EU is currently more than 65% dependent on imports from China for 22 CRMs that are key to the defence industry. For ten of these CRMs the dependency is virtually 100% (European Commission 2020: 19). Moreover, these primary products are not only in such high demand due to their use in the manufacture of defence equipment, but are also indispensable for renewable energy generation and electric vehicles as part of the mandatory EU Green Deal and in the

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context of global digitalisation. This competition for CRMs has multiplied demand in the last few years (Reisch 2022: 1) and exacerbated the existing problem of limited supply. Despite the severe shortage on the market and the multiplication of demand that has already occurred, the demand is forecasted to at least triple again by 2060 at a high level (Küblböck 2023: 4; European Commission 2020: 9). After years in which securing raw material supply chains did not constitute a priority for the EU, the Covid pandemic, the trade war between China and the USA, the Russian war of aggression against Ukraine and China's "admonishing neutrality" (Carry et al. 2023:1) towards the latter acted as “watershed” (Seaman et al. 2022: 19) events leading to political reconsiderations (Maihold 2022: 1). In times of a growing "geopoliticization" (Ringhof/Torreblanca 2022: 21) of trade relations, in which Chinese President Xi Jinping announced his intention to use his supremacy in terms of CRMs as a “powerful countermeasure and deterrent capability” (European Commission 2023), the EU was forced to take action to prevent itself from getting under constant security threat of coercion by China (Carry et al. 2023: 1).

Following initial steps such as the first EU-wide raw materials initiative in 2008 or the first and then constantly updated list of CRMs in 2011(Küblböck 2023: 7), it was above all Ursula von der Leyen's "Geopolitical Commission" (Ringhof/Torreblanca 2023: 3) that brought the new “de-risking” (European Commission 2023) strategy into play in conjunction with the concept of Open Strategic Autonomy. These overarching policy concepts were followed by other concrete and abstract arrangements such as the European Chips Act, the Critical Raw Material Act, the European Security Strategy and the Global Gateway initiative. Thus, these measures will serve as a centrepiece of the following analysis. Hereby, examining the effects of the EU measures aimed at reducing its supply chain dependency on China and its impacts on the supply security of the defence industry.

2. DEPENDENCIES IN THE EU´S DEFENCE SUPPLY CHAIN SECTOR ON CHINA

The politically and strategically important EU defence industry requires a wide variety of specific raw materials and intermediate products for the production of any competitive modern weapon system (Pavel/Tzimas 2016: 38). Due to various circumstances, enormous risks for the European defence industry in the supply chain from China exist, both in the supply of raw materials and in the processing of specialised upstream products (Findeisen/Wernert 2023: 1). This import dependency of the European defence industry on China is exacerbated both by internal sectoral competition due to the announced green and digital transformation and by global competition for unrestricted access to these raw materials and processed goods from them (Girardi et al. 2023: 1-48).

Due to its strategic importance within the security and defence provision for the EU, the military sector must function seamlessly and requires an uninterrupted supply of raw materials and intermediate products (European Commission 2020: 70). Only the most specialised raw materials and the most innovative components will guarantee competitive weapon systems that are decisive in the event of conflict due to direct effects on precision, fuel consumption, manoeuvrability, and vigour (European Commission 2020: 70-72). Therefore, the EU Commission's Joint Research Centre identified 39 raw materials and 47 processed goods such as alloys, compounds and composites materials for the EU defence industry having a critical supply chain dependency (Pavel/Tzimas 2016:3). However, this analysis only refers to CRMs which are defined as “raw materials of high economic importance for the EU, with a high risk of supply disruption due to their concentration of sources and lack of good, affordable substitutes" (European Council 2023). Among the identified CRMs of the EU, this study focuses on those raw materials 1) that are of particular relevance to the EU defence industry, 2) whose EU import dependency exceeds the 65% criterion from a single country stated in the EU CRMA and 3) China being that single country of EU import dependency. After these restrictions, 22 CRMs still meet all three criteria of import dependency on China on the one hand and overriding importance in the EU defence sector on the other.

This one-sided dependency of the EU is part of a decade-long geoeconomic strategy of China which was based on the Chinese government's ideas of state investment, low labour costs and environmental regulations as well as rapid licensing which resulted in achieving the dominant global position in a variety of CRMs (Cohen 2023). Consistently high government subsidies to mining companies acted as a lubricant, as other global competitors were forced out of the market due to unnaturally low prices set by Chinese corporations (German Council of Economic Experts 2022: 377). As a result, this "aggressive posture to undermine rivals" (Cohen 2023) systematically disincentivised new projects by other players (Cohen 2023), so that the mostly state-controlled Chinese mining companies soon held considerable market power (Leonard 2021: 16). In addition to that, China's active pricing policy, which distorts world market prices and destroys the economic viability of new projects in other countries, has not changed until today (German Council of Economic Experts 2022: 376-381). The strong concentration in the global share of CRM mining was supplemented by strategic decisions with regard to the downstream processing and refining of CRMs (Girardi et al. 2023: 28). Due to its dominance over irreplaceable raw materials, China is expected to become the global frontrunner in highly specialised products such as semiconductors, catalysts and magnets by 2030 (Sahin/Barker 2021: 40) as a result of its Made in China 2025 industrial strategy (van den Abeele 2021: 9), which aims to take the leadership in strategic high-tech sectors. This intensifies the EU's existing dependency, as the today´s diversified trade partners will no longer be the systemically like-minded states such as Taiwan or South Korea, but the “systemic rival” (German Council of Economic Experts 2022: 387). Due to the central significance of semiconductors for the military strength (German Council of Economic Experts 2022: 377), which are also referred to as the “new oil” (Mayer/Lu 2022: 3) or the "most sought-after commodities" (Patrahau et al. 2023: 5), the EU's dependence on China is an immense security threat.

The aforementioned concentration of various steps in the processing of several CRMs, which are of great importance to the EU's military sector, is significant because the authoritarian Chinese government has direct access to the export policies of state-controlled mining and processing corporations which are representing 90% of the Chinese mining capacities (Girardi et al. 2023: 10). Thus, the Chinese government´s decisions on CRM disposability have a massive impact on the import-dependent countries such as the EU. Especially, since the Chinese government "began to weaponize existing trade and infrastructural interdependence"(Mayer/Lu 2022: 3), supply chain risk for the EU´s defence sector is considered as higher than ever. Think-tanks have identified 123 coercive cases between 2010 and 2022 while stating that many cases are not reported on by states due to their anxiety towards Chinese retaliation measures (European Parliament 2022: 4). This is evident through an active raw material production and export restriction policy by means of export quotas in certain countries dependent on China (Giradi et al. 2023: 28). Since 2009, China has applied the largest share of all global raw material export restrictions globally (Patrahau et al. 2023: 14). In the last 15 years, the number of imposed export controls by China on CRMs has increased fivefold (Cohen 2023).

Next to general CRM quantitative tightening, China also uses its superiority for direct, targeted geopolitical reactions to specific geopolitical events (Kratz et al. 2022:6). This started with

China's embargo on rare earth exports to Japan in 2010 (Cohen 2023) which will be elaborated at a later stage. In addition, raw material-dependent EU countries already became the target of China's coercive policy (Kratz et al. 2022:6). China has already used its asymmetric raw material dominance by restricting the export of natural graphite, which is associated with high risks in the supply chain, from 2020 in order to strengthen the market power of Chinese enterprises at the expense of European high-tech enterprises that were thenceforth unable to compete. However, Lithuania, which was exposed to enormous tensions with China after opening a 'Taiwan Representative Office' in Vilnius in 2021, experienced the most extensive coercive measures by China in the EU. As a result of being excluded from the Chinese customs system, China's foreign trade with Lithuania declined by around 90%, which also brought trade in CRMs to a virtual standstill (European Parliament 2022: 5). In addition, companies from third countries trading with Lithuania were warned of secondary sanctions, which were actually enforced in case of violation (Reynolds/Goodman 2022). Other sanctions were taken against EU member Sweden and like-minded states such as South Korea and Australia (Mc Gregor 2022).

3. ASSESSMENT OF EU SUPPLY CHAIN RISK REDUCTION COUNTERMEASURES

The measures launched by the EU are all designed to achieve greater autonomy with regard to the supply of CRMs. In the following, the ECA, the CRMA, the ESS and the Global Gateway initiative will be assessed in regard of their effects on supply chain dependence reduction.

The ECA addresses the dependence of many EU industrial sectors on the supply of semiconductors. They have become indispensable for modern weapons systems in the defence industry. The starting position for the EU is extremely unfavourable, as it is lagging behind the USA and East Asian countries due to a lack of know-how. In the overall assessment of the ECA, however, it must be noted that although the importance of the industry, not least for the defence sector, has been highlighted, the financial resources involved remain considerably too limited to pose a challenge to international competition. The EU's subsidy volume under the ECA is well below that of comparable programs in competing countries including the USA, China and South Korea and is thus likely to fail to achieve the goal of building up sufficient production capacity, but also lacks a plan for foreign companies with know-how that guarantees long-term economic profitability in times of price fluctuations and overcapacity.

The CRMA, which aims to secure the supply chains for CRMs, including for the defence industry, by diversifying the sources, uses concrete and ambitious target benchmarks by 2030. These benchmarks, whose specific levels have not been declared by the EU, are to be achieved through simplified and shortened application procedures for mining projects within the EU and mandatory requirements for recycling quotas in the member states as well as international diversification of supply chains. It must be criticised that the lack of EU funding within this measure has not yet led to the involvement of the private sector, which is crucial for the transformation. The EU mining market remains unattractive for mine operators without certain financial guarantees from the EU, particularly in light of the high labour and environmental regulations. In order to improve the CRMA, the EU must ensure the financing of the development of mining facilities within the EU and also protect the long-term financial security of mine operators, as the continued existence of European extraction sites will be threatened by price manipulation on the global market by Chinese state-owned companies. Only with a long-term sharing of the operation risk between institutions, governments and companies, an extensive uptake of mining within the EU can be assured.

By introducing stricter measures for FDI and export controls, the ESS ensures that less knowledge, expertise and capital from EU companies migrates to China and benefits the military capabilities of its rival. Instead, this measure strengthens EU supply chains and addresses security threats such as coercive measures and bottlenecks caused by China through the formation of a unified response. Unintended by the EU, China's aggressive coercive measures practices against Japan, Sweden or Lithuania encouraged a substantial part of the private sector to rethink and voluntarily redirect its investments and supply chains to countries with more predictable trade policies. Nevertheless, the ESS does not solve the fundamental problem of the continuing massive supply chain dependency on China in the defence industry.

The most extensive measure in financial terms is the EU's Global Gateway strategy. With an investment volume of €300 billion, international partnerships should be concluded in order to create a diversified trade, investment and supply chain infrastructure for the EU. Although it has not been officially stated, the intention is to curb China's expanding political and economic influence through the BRI. Securing raw material supply chains through international diversification is an intelligent and logical step for the EU. The numerous free trade agreements with a large variety of resource-rich nations that were renegotiated or updated with raw materials chapters within a short period of time were at first promising. On closer inspection, however, the negative aspect is that most of the trade agreements only mean marginal improvements for EU imports due to the already low tariffs on raw materials. The funding also remains questionable, even though it is already significantly lower than China's reference project BRI. On the one hand, the EU budget, consisting primarily of financial commitments that have already been made but have been rededicated, is not very conducive to innovation and, on the other hand, the other half of the estimated €300 billion investment sum still has to be raised from the private sector. It remains questionable whether the EU intends to take its ambitions of diversifying supply chains through infrastructure investment to heart, given the significantly lower investment sums and number of projects compared to China's BRI.

4. ROLE MODEL JAPAN: THE ONLY SUCCESSFUL CRM DECOUPLING STRATEGY

None of the EU's securitising measures mentioned, despite the much-cited severity of dependence on an over-dominant rival, have reached the proportions that Japan was willing to take after it was blackmailed by China through an import ban on CRMs in 2010 following geopolitical tensions. After being exposed to an immense price shock for the CRMs necessary to sustain its economy and defence capability, Japan decided to take a drastic and costly measure to reduce its future dependence on China (Cohen 2023). It pursued the nationalisation idea in resource management and established the Japan Organization for Metals and Energy Security (JOGMEC) (Levinger 2023: 4). With this state agency, Japan provides massive financial assistance, investment guarantees and expertise to corporations in order to develop raw material reserves around the world. JOGMEC can provide up to 50 percent of the development costs in the form of guarantees or investment grants, which creates a clear monetary advantage for the companies benefiting from this due to low interest rates and the high creditworthiness of the state as lender of last resort (Goldthau 2013). For Japan's security of supply of CRMs, it meant that massive government-backed investment led to establishing the first rare earth processing line outside China with the help of the Australian mining company Lynas (German Council of Economic Experts 2022: 391). After more than a decade of enormous subsidy costs for the Japanese state, the country's dependence on China for rare earths was reduced from over 90% to around 50% (German Council of Economic Experts 2022: 391).

Although other countries such as South Korea have since followed Japan's example (Levinger 2023: 4), the EU has not announced comparable measures to make CRMs more secure, despite its extensive discussion of the supply chain problem. The duration and cost of Japan's JOGMEC initiative clearly show that despite the considerable urgency due to the recent confrontation with China, even after a decade of Japan's autonomisation efforts, the country´s critical dependence on China still persists. Consequently, despite all the EU's diversification efforts as part of the Global Gateway strategy, which is by no means only aimed at reducing dependence on rare earths, let alone all CRMs, it is unlikely to be sufficient to bring about a significant reduction in potential defence sector supply chain disruption.

5. CONCLUSION

In 22 CRMs and a large number of processed high-tech products, which are irreplaceable for the EU's defence industry and therefore also its defence capability, the EU is more than 65% dependent on China in at least one production stage. Against the backdrop of coercive measures announced by Chinese President Xi Jinping and already implemented against EU states by means of asymmetric trade dependencies, the Commission was forced to adopt countermeasures to protect future supply chains. In times of a digital, green transformation and the resulting surge in international demand for CRM, these measures must withstand the more assertive and coercive Chinese policies.

Due to the aforementioned financial, economic and political reasons, the prospects for a significant improvement in self-sufficiency or international supply chain architecture with regard to CRMs and processed high-tech products for the defence industry are minimal. This is explained by the fact that the EU measures do not specifically target CRMs, which pose a particular risk of supply chain disruption for the defence industry. These measures, which are relatively underfunded compared to other initiatives by international players, will not succeed in keeping pace with competitors or even challenging China's dominant position. The measures introduced contribute to concealing urgent supply chain risks, but do not solve the long-term needs of the defence industry. A reluctance to invest heavily in long-term projects has reinforced the primacy of economic efficiency over sustainable security interests. Thus, despite the policy emphasis on supply chain security, the EU has not opted for a far-reaching measure like Japan, which implemented a costly and long-lasting policy after being targeted by China's coercive measures.

As the EU does not have a comparable approach and its own measures are unlikely to make a significant difference in terms of strategic autonomy of supply chains, it can already be assumed that the EU will remain dependent on Chinese supplies for the next one to two decades due to the long lead times for future CRM autonomy efforts in the defence industry. As a result, it can be concluded that the EU will not be able to increase its strategic autonomy sufficiently in relation to its defence industry supply chain. Despite the securitising measures introduced, dependence on China will remain significant in both the short and long term.

References

[1] Carry, Inga, Nadine Godehardt and Melanie Müller, (2023) “The Future of European-Chinese Raw Material Supply Chains”, No.27, May 2023, pp 1-8.

[2] Cohen, Jared, (2023) “Resource realism: The geopolitics of critical mineral supply chains”, Goldman Sachs, 13 September 2023, accessed 15 February 2024. https://www.goldmansachs.com/intelligence/pages/resource-realism-the-geopolitics-of-critical-mineral-supply-chains.html.

[3] European Commission, (2020) “Critical Raw Materials for Strategic Technologies and Sectors in the EU – A Foresight Study”, pp 1-98.

[4] European Commission, (2023) “Speech by President von der Leyen on EU-China relations to the Mercator Institute for China Studies and the European Policy Centre”, Brussels, 30 March 2023, accessed 15 February 2024.
https://ec.europa.eu/commission/presscorner/detail/en/speech_23_2063.

[5] European Parliament, (2022) “China´s economic coercion – Evolution, characteristics and countermeasures”, European parliamentary research Service, Briefing, November 2022, pp 1-12.

[6] Findeisen, Francesco and Yann Wernert, (2023) “Meeting the costs of resilience: The EU´s Critical Raw Materials Strategy must go the extra kilometer”, Hertie School – Jacques Delors Centre, Policy Brief, June 2023, pp 1-10.

[7] German Council of Economic Experts, (2022) “Competitiveness in Times of Geopolitical Change – National Productivity Report 2022”, published as Chapter 7 of the Annual Report 2022/23, pp 359-419.

[8] Girardi, Benedetta, Irina Patrahau, Giovanni Cisco and Michel Rademaker, (2023) “Strategic materials for defence – Mapping European industry needs”, The Hague Centre for Strategic Studies, January 2023, pp 1-48.

[9] Goldthau, Andreas, (2013) “Japan Oil, Gas and Metals National Corporation (JOGMEC)”, bpb, 1 March 2013, accessed 16 February 2024.
https://www.bpb.de/themen/wirtschaft/energiepolitik/152949/japan-oil-gas-and-metals-national-corporation-jogmec/.

[10] Kratz, Agatha, Charlie Vest and Janka Oertel, (2022) “Circuit Breakers: Securing Europe´s Green Energy Supply Chains”, Council on Foreign Relations, Policy Brief, May 2022, pp 1-14.

[11] Küblböck, Karin, (2023) “Von der Rohstoffinitiative zum Critical Raw Materials Act - Rohstoffstrategien der Europäischen Union”, Österreichische Forschungsstiftung für Internationale Entwicklung, July 2023, pp 1-17.

[12] Levinger, Hannah, (2023) “Der EU Critical Raw Materials Act: Weichenstellung für den Standort Europa”, KfW Research Fokus Volkswirtschaft, Nr. 421, March 2023, pp 1-6.

[13] Maihold, Günther, (2022) “Die neue Geopolitik der Lieferketten”, Stiftung Wissenschaft und Politik, Nr. 45, July 2022, pp 1-8.

[14] Mayer, Maximilian and Yen-Chi Lu, (2022) “Digital Autonomy? Measuring the Global Digital Dependence Structure”, Center for Advanced Security, Strategic and Integration Studies, Bonn, pp 1-29.

[15] Patrahau, Irina, Lucia van Geuns and Michel Rademaker, (2023) “European tank storage and changing geopolitical landscapes”, The Hague Centre for Strategic Studies, June 2023, pp 1-19.

[16] Pavel, Claudiu and Evangelios Tzimas, (2016) “Raw materials in the European defence industry”, JRC Science for Policy Report, European Commission, pp 1-120.

[17] Reisch, Viktoria, (2022) “The Race for Raw Materials”, Stiftung Wissenschaft und Politik, No.1, May 2022, pp 1-8.

[18] Reynolds, Matthew and Matthew P. Goodman, (2022) “China´s Economic Coercion: Lessons from Lithuania”, Center for Strategic and International Studies, 6 May 2022, accessed 16 February 2024. https://www.csis.org/analysis/chinas-economic-coercion-lessons-lithuania.

[19] Ringhof, Julian and Jose Ignacio Torreblanca, (2022) “The Geopolitics of Technology: How the EU can become a Global Player”, European Council on Foreign Relations, Policy Brief, May 2022, pp 1-37.

[20] Sahin, Kaan and Tyson Barker, (2021) “Charting a Path for Europe in Times of Major Technological Disruption”, German Council on Foreign Relations, DGAP Report, No. 6, April 2021, pp 1-43.

[21] Seaman, John, Francesca Ghiretti, Lucas Erlbacher, Xiaoxue Martin and Miguel Otero-Iglesias, (2022) “Introduction: Europe Debates (or doesn´t) its Dependence on China, in: Dependence in Europe´s Relations with China – Weighing Perceptions and Reality”, April 2022, pp 12-24.

[22] Van den Abeele, Eric, (2021) “Towards a new paradigm in open strategic autonomy?”, European Trade Union Institute, Working Paper 2021.03, pp 1-62.

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INTELLIGENT SWARM COORDINATION IN A COMS-DENIED SURVEILLANCE LANDSCAPE

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Abstract

In this paper we take a step towards UxV-swarm integration in mosaic warfare by pinpointing critical challenges in civil and military implementation of swarms in communications denied areas. A simulation study is performed to examine the effects of Swarm efficiency under different levels of coms-denial and the results highlight the need for robust solutions relying on decentralized decision making in coms-denied areas while exemplifying promising capabilities of UxV-swarms for autonomous Intelligence, Surveillance and Reconnaissance tasks.

Keywords

UxV Swarms, Communication Denial, Mission Planning, Mosaic Warfare, Autonomous systems

1. INTRODUCTION

The future of warfare is complex and Mosaic Warfare is one concept of future warfare [1], [2], that proposes to revolutionize military strategy by combining different operational fragments, such as intelligence, decision making and control into an interconnected system; in a form resembling a mosaic. This approach amalgamates diverse platforms to overwhelm adversaries across multiple domains through a highly complex composition of forces, dynamically incorporating both manned and unmanned systems. The heightened complexity decreases the enemy's ability to predict actions on the opposing side and construct appropriate counteractions. By distributing resources and decision-making across numerous units and domains, forces can efficiently achieve a concentrated effect, without utilizing overwhelming mass [3]. This redefines modern warfare by prioritizing flexibility and interconnectedness over traditional force concentration tactics. Unmanned platforms, for simplicity here referred to as UxVs, acting together in swarms play a pivotal role in such visions. However, achieving such battlefield presence, whether for offensive, defensive, or ISR purposes, presents challenges to existing swarming tactics, which is compounded by the coordination and communication requirement across domains – particularly when aiming for a high degree of autonomy to achieve localized superiority through a complex delivery of effects.

Implementing Mosaic Warfare thus poses clear challenges in terms of research, necessitating the development of technology as the platforms, communication, and command and control means are not existent or insufficiently mature for operations. Furthermore, literature tends to focus on single-domain applications with homogeneous platforms [4], [5], [6], with limited attention given to multiple domains [7] or heterogeneous platforms. The gaps become further apparent when considering concepts for addressing systems-of-systems comprising both attritable and non-attritable platforms.

Mosaic warfare is a promising concept that harnesses the potential of unmanned systems operating seamlessly in concert across multiple domains. The aim of this research paper is therefore to identify critical technology gaps and initiate the development of a unified multi-

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domain framework for swarm operations in the context of mosaic warfare, emphasizing coms-denied operational environments.

2. STATE-OF-THE-ART

Keeping this in mind, our initial focus is to examine the background of swarm technology and identifying critical technologies and approaches. We then organize this information to illustrate how swarm technology aligns with the principles of Mosaic warfare and addresses the inherent challenges in deploying UxVs for operations, particularly in terms of communication and control/coordination.

Path planning and decision-making for a single platform is a widely explored topic in literature, and as such many solutions exist. However, swarming UxVs is fundamentally multi-platform, which sees a much sparser representation in the literature. A first formulation of the distributed behavioral model for controlling agent swarms can be traced back to 1987, where C. W. Reynold [8] proposed this for computer animation. Taking inspiration in nature, Reynold imitated complex flocking behavior by assigning simple logic to agents, only reacting to the movement of their nearest neighbors. Reynolds work later motivated the development of the popular Particle Swarm Optimization algorithm (PSO) [9] for solving non-linear equations. A multitude of different modifications to the PSO algorithm have since been proposed. C.J.A. Bastos-Filho et al. [10] introduce the MOPSO-CDRS algorithm, for solving multi-objective coverage problems. By dynamically altering the optimization objective based on the characteristics of the Pareto front, partitioning the swarm and distributing objectives among sub-swarm, they show the algorithm dominates comparable approaches. In [5] the authors propose a graph-based swarming algorithm for surveillance. When a target of interest is detected, the swarm is partitioned, only utilizing a subset of the resources for dealing with the target. Their sub-swarm generation algorithm facilitates inter-communication between sub-swarms by ensuring team connectivity. For the basic PSO algorithm to work, full communications must be present. However, especially in military operations, communication might be limited. In [11] UAV communication is cast as an energy-conservation problem. By inducing the swarm to self-organize into clusters, each sub-swarm designates a communications agent which is tasked with relaying information from its cluster. This limits the number of agents expending large amounts of energy for information-transfer by focusing on intra-cluster communications. Though not explicitly for UxVs, Deng [12] explores a leader-follower consensus approach for multi-agent communication under partial coms-denial. They cast the communications network as a connected graph, and formulate the problem as a control system, subsequently showing how communication delays can be mitigated using a switching controller. In [13] the authors propose to operate quadrotor UAV swarms in a coms-denied environment using decentralized control. They approach simultaneous coverage and tracking using reinforcement learning, and by also encoding location, speed, and area coverage information, their RL mechanism offloads the bulk of computations to an offline process. This also enables each agent to estimate the system state and decision model of neighboring agents, and thus better incorporate hidden information into the decision process.

Lastly, [4] examine the robustness of autonomous UAV swarms, proposing a non-destructive attack vector: By introducing a small number of rogue UAVs into a swarm, the swarm can be redirected by exploiting the distributed behavioral model. They successfully defend against a Gray Wolf Optimizer [14] based attacking swarm, corrupting the swarm's optimization problem by broadcasting biased information. Though their approach relies on open communication channels, and is shown to be ineffective on the Slime Mould Optimizer [15], this disruption technique has merit in the design of robust distributed decision-making.

Examining current-state swarm research reveals several critical challenges vital to the operational integration of swarms of UxVs in mosaic warfare. Amongst these are strategic selection of operational domain (land, air, sea, space), precise description of operational objectives, as well as consideration of the composition (homogenous vs. heterogenous) of the deployed platforms within each selected domain. In addition, emphasis should be put on methodologies employed to achieve the desired effects, including tactical, strategic, and technological synergies across multi-domain platforms as well as an assessment of the communication level permitted / feasible in the given situation. As a frame of reference Table 1 delineates three connectivity levels and corresponding agent scenarios.

Table 5. Swarming communication levels.

Level 2: *Global Communication*	***Level 1:*** *Local Communication*	***Level 0:*** *No Communication*
Agents can communicate freely. Decision-making can be offloaded to a centralized intelligence and can be based on global information. [8], [9], [10], [11]	Agents can communicate in spatial neighborhoods. Decision-making needs to be distributed among agent groups and can only be based on localized information. [4], [6], [13]	Agents cannot communicate. Decision-making needs to be distributed among agents and can only be based on hyper-localized information.

With the varying levels of communication and current state of research in mind the three following topics are identified as critical to address. Coordination: Planning meaningful movements with many agents without communication while simultaneously discouraging inefficient behaviour, forces each individual agent to make decisions based solely on local situational awareness. Path Planning: Without the ability to update information between agents, collaborative objectives such as reconnaissance, target acquisition, and detection avoidance, requires alternative communication channels. Adaptability: New information might require replanning a mission. With changing communication conditions, the swarm must adapt without complete knowledge of the state of the swarm.

In coms-denied situations, agents resort to decentralized decision-making, relying solely on individual situational awareness. This raises performance concerns shifting from level 2 to levels 1 and 0 communications. However, decentralized decision-making not only facilitates complex behaviour without global communication, but also enhances scalability by accommodating additional agents without added computational strain from centralized processes.

3. PROBLEM FORMULATION AND ALGORITHM DEVELOPMENT

With these levels of communication and decision-making paradigms in mind, a tiered decision-making process with associated decision mechanisms is defined in Figure 37.

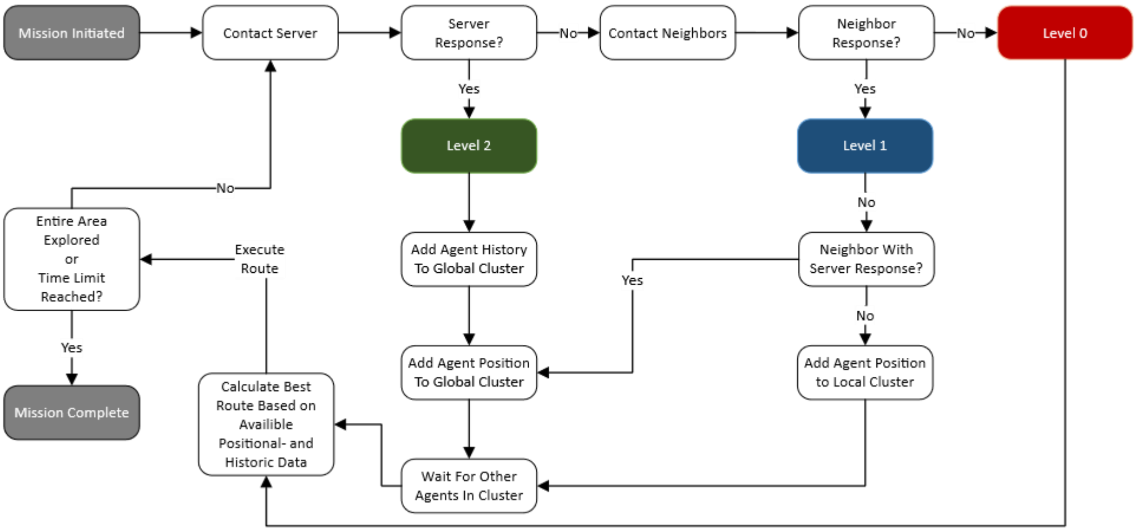

Figure 37. Proposed tiered decision-making process.

Using this as a basis, we formulate a simplified illustrative example for a single-domain surveillance scenario. The surveillance problem for a swarm of UAVs through multiple decision cycles (depending on coms-level) can essentially be reduced to selecting the set of manoeuvres for each UAV that maximizes the total new landmass inspected, while complying with operational constraints.

$$Max_{x \in X} |C_{T_{max}}| \qquad s.t.$$

1) $D^2_{t+1} = f\left(D^2_t, x_{d,t}\right) \quad \forall d \in D^2 \ \wedge \forall t \in T \quad (maneuvarability\ constraint\ in\ D^2)$
2) $d^0_{t+1} = f\left(d^0_t, x_{d,t}\right) \quad \forall d \in D^0 \ \wedge \forall t \in T \quad (maneuvarability\ constraint\ in\ D^0)$
3) $if\ \exists d_i \in D^2 : \left|\left|d_{i,t} - d_{j,t}\right|\right|_2 \leq R_{com} \ \Rightarrow \ d_{j,t+1} = f\left(D^2_t, x_{d,t}\right) \quad \forall\ d_j \in D^1$

$$(man - coms\ constraint\ in\ D^1\ with\ D^2\ contact)$$

4) $\left|\left|d_{i,t} - d_{j,t}\right|\right|_2 \leq R_{com} \ \Rightarrow \ d_{j,t+1} = f\left(d_{i,t} \cup d_{j,t}, x_{d,t}\right) \quad \forall d_j, d_i \in D^1 \ \wedge \ i \neq j$

$$(coms\ constraint\ in\ D^1)$$

5) $D_0 = UAV\ depot \quad \forall d \in D \quad (initialization\ constraint)$

Where $|C_{T_{\max}}|$ is the norm of covered segments by all the UAVs in communication level 2 at time T_{max}. Note: $C_t = \bigcup_{d \in D^2} C_{d,t}$ indicates the combined set of segments covered by the swarm in full communication, that is, information from UAVs in D^1 is not combined with the central knowledge until it moves to a position in full communication. $T = \{1,2,\ldots,T_{max}\}$ denotes the set of decision cycles with running index t, where $T_{\max}$ is the time horizon.

Table 6: Notation table

Notation	Description
$T = \{1,2,\dots,T_{max}\}$	The set of decision cycles with running index t, where $T_{\max}$ is the time horizon.
$D_t = \{d_{1,t}, d_{2.t}, \dots, d_{N,t}\}$	The set of all UAVs and their position at time t
D^2, D^1, D^0	The subset of UAVs either in coms-level 2,1, or 0. This set is a function of the swarms' locations. Note, $D_t = D_t^2 \cup D_t^1 \cup D_t^0$
D_0	The starting position of all UAVs are forced to be that of a UAV depot
$C_{d,t}$	The segments of the map covered at time t for UAV d.
$X = \{x_{D,1}, x_{D,2}, \dots, x_{D,T_{max}}\}$	The set of all decisions (manoeuvres performed) by the swarm D for all decision cycles T.
$f()$	The function that ensures that future positions for UAVs correspond with the manoeuvre performed $x_{d,t}$ at time t. Note, the maneuver can be based on the combined information of the swarm in D^2, a cluster, or only itself.
R_{com}	The radius within UAVs in $D^1 \cup D^2$ can communicate with each other
R_{obs}	The radius within UAVs can observe the map
R_{noise}	The radius within a noise tower that UAVs are affected by coms-denial. If a UAV is within radius of a single tower it is in coms-level 1, if it is within radius of two or more it is in coms-level 2. The default is level 0.

Some central assumptions for this model are: (1) The UAVs fly at different altitudes; therefore, consideration of collision avoidance can be omitted (2) the UAVs' energy consumption and the constraint on the final position of the UAVs is not considered (3) The targets' behaviour is completely random. (4) The map structure is not known a priori, and consequently, whether a UAV is in D^2, D^1, and D^0 is similarly unknown a priori. Note the covered segments for each UAV, $C_{d,t}$, is defined as those segments (or indices in a grid-like map) that have an L_2-norm less than R_{obs}, the distance with which a platform can observe.

The solution approach for selecting a set of manoeuvres for the considered set of UAVs is for now to generate a larger set of random manoeuvres for a given decision horizon and then to evaluate the expected collaborative coverage of that solution on the decision horizon. A larger decision horizon will automatically yield a more sophisticated behaviour, but with a significant computational load, this decision horizon should be specified with care. To limit the computational load, the decision within each cluster is taken hierarchically and it is based on the evaluation of the cluster. The sets under consideration are:

- The single combined set of UAVs in D^2 with D^1 UAVs that are neighboring a D^2 UAV. If a D^1 UAV is then neighboring a member of that set, then we add that to the set. This procedure is iterated until no more D^1 UAVs are neighboring any from the fully connected set.
- The (multiple) unique sets of D^1 UAVs that are neighboring each other. If they are neighbors, they decide on a collaborated manner with the combined knowledge of the set where they want to go.

- The single D^1 UAVs without any neighbors and any D^0 UAVs. These are considered independently. That is, they will only consider themselves and their own map history in the search for a solution.

4. SIMULATION AND PERFORMANCE ANALYSIS

The simulation environment considers a 1024-by-1024 lattice graph, where UAVs can move around with a certain distance for each time unit. For simplicity, we assume the UAVs traverse a distance of 30, but it should be defined based on the specifications of the vehicle in relation to the map representation and the real-world relation. The time horizon is set at 100 time units. Furthermore, we assume the R_{obs} distance, indicating the radius with which UAVs can identify targets to be 50. On the map 20 noise towers are generated, they could also symbolize valleys where communication is not feasible. If a UAV is not within an R_{noise} distance in L_2-norm from the center of a noise tower, it is a part of the D^2 set with full communication. If it is within a single noise tower, the UAV will be considered as part of the D^1 set of UAVs, unless it has a neighbor that is in the D^2, then it is also considered as part of the D^2 set. If it is within an R_{noise} distance, then it is considered as part of the D^0 set that is it is fully coms-denied. We consider a scenario where we must route a set of 10 UAVs. Moreover, there are 3 enemy bases that spawn targets that we want to locate. All simulations are run on a workstation with a 1.6 GHz Intel i5-8250 processing unit.

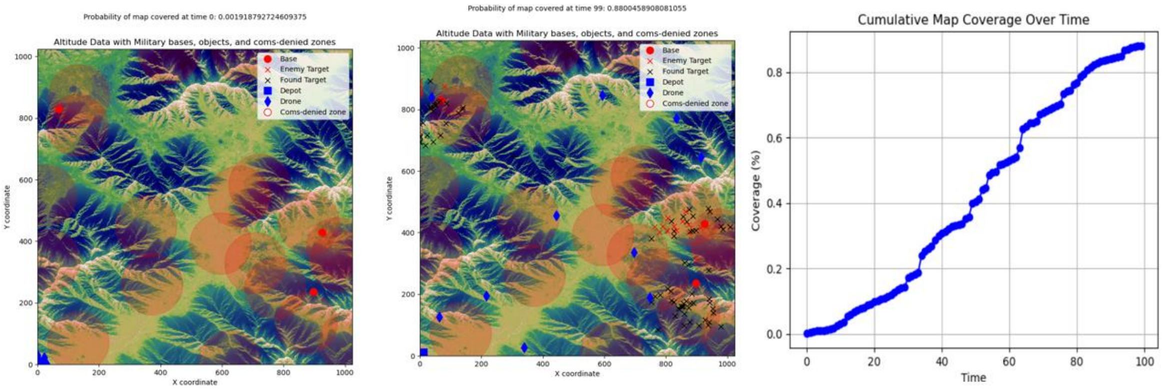

Figure 38: The map scenarios for t_0 and T_{max} and the cumulative coverage.

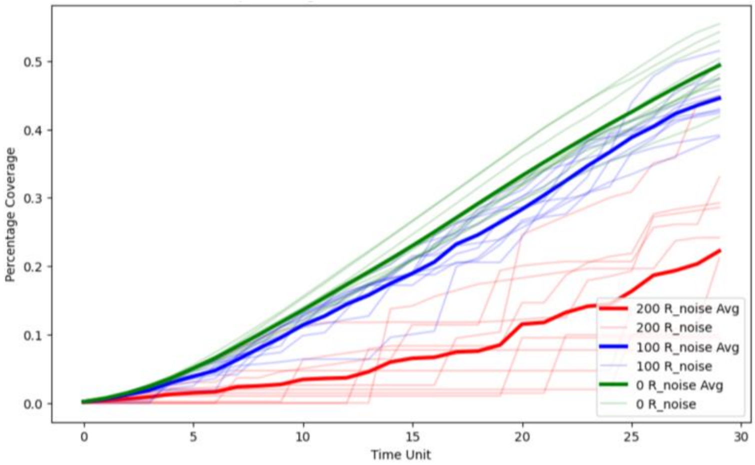

Figure 39: The cumulative coverage for three different levels of coms-denial scenarios

When the level of coms-denial increases, we see that the swarm continues to operate with proficiency, establishing communication clusters and reporting back to the central. The interaction with the central even for higher levels of communication denial is paramount, especially as we evaluate the coverage based on its knowledge. For certain problem scenarios, the entire swarm is within a fully coms-denied zone and can consequently not return any information back before it traverses to a zone with less disturbance. For these reasons, we will see more jumps in the central's knowledge of the coverage in scenarios with more coms-denied zones. As a construct of the routing solution approach and the complexity of a scenario with no noise (that is a full communication scenario is $R_{noise} = 0$), certain levels of coms-denial can actually lead to a better performing swarm as it is easier to reach a local optimal solution for a small clusters than it is for a large one. Consequently, the interplay between routing solution approach, communication and collaboration protocol is of high importance.

5. CONCLUSION AND FUTURE WORK

Inspired by Mosaic Warfare, our research integrates diverse operational fragments into a seamless, interconnected system. By leveraging the complexity and dynamic nature of UxV swarms, we move towards achieving capabilities of envisioned in Mosaic Warfare by emphasizing unpredictability and flexibility. The development and implementation of a framework for a distributed solution approach, leveraging the local knowledge of the individual UxV or subsets of the swarm is the main contribution of the work. This research demonstrates this capability through an example from the air domain with UAV swarms in communication-denied environments. The research findings emphasize the significance of autonomous decision-making within UxV swarms, facilitating efficient operations independently of centralized communications. These insights have relevance across multiple operations and domains. Moreover, our observations indicate that even in communication-denied environments, UxV swarms can accomplish efficient operations.

Future research should focus on a number of key challenges. First, to extend the effort to cover the coordination of multiple domains. Second, to develop a distributed solution approach that depend on the compute capability on the platform or set of platforms e.g. by splitting the solution problem into manageable sub-problems solved collaboratively by the drone set. Third, to integrate with manned systems.

References

[1] “DARPA Tiles Together a Vision of Mosaic Warfare.” Accessed: Mar. 28, 2024. [Online]. Available: https://www.darpa.mil/work-with-us/darpa-tiles-together-a-vision-of-mosiac-warfare

[2] D. Qi, J. Zhang, X. Liang, Z. Li, J. Zuo, and P. Lei, “Autonomous Reconnaissance and Attack Test of UAV Swarm Based on Mosaic Warfare Thought,” in 2021 6th International Conference on Robotics and Automation Engineering (ICRAE), Guangzhou, China: IEEE, Nov. 2021, pp. 79–83. doi: 10.1109/ICRAE53653.2021.9657810.

[3] D. A. Deptula, H. R. Penney, L. A. Stutzriem, and M. A. Gunzinger, “RESTORING AMERICA’S MILITARY COMPETITIVENESS: Mosaic Warfare.” The Mitchell Institute for Aerospace Studies, Sep. 2019. Accessed: Mar. 28, 2024. [Online]. Available: https://mitchellaerospacepower.org/restoring-americas-military-competitiveness-mosaic-warfare/

[4] J. Simonjan, S. R. Probst, and M. Schranz, “Inducing Defenders to Mislead an Attacking UAV Swarm,” in 2022 IEEE 42nd International Conference on Distributed Computing Systems Workshops (ICDCSW), Bologna, Italy: IEEE, Jul. 2022, pp. 278–283. doi: 10.1109/ICDCSW56584.2022.00059.

[5] M. M. Shahzad, M. H. Asad, M. Haris, H. Munawar, and M. H. Yousaf, “Formation Control and Sub-Swarm Generation of Multirotor UAVs,” in 2023 International Conference on Robotics and Automation in Industry (ICRAI), Peshawar, Pakistan: IEEE, Mar. 2023, pp. 1–7. doi: 10.1109/ICRAI57502.2023.10089546.

[6] A. Ali, M. M. Shahzad, A. H. Qureshi, M. Shaukat, and M. H. Yousaf, “A Decentralized Pattern Formation and Navigation Approach For Swarms: Multi-UAV Perspective,” in 2021 International Conference on Robotics and Automation in Industry (ICRAI), Rawalpindi, Pakistan: IEEE, Oct. 2021, pp. 1–6. doi: 10.1109/ICRAI54018.2021.9651460.

[7] Y. Khosiawan, A. Khalfay, and I. Nielsen, “Scheduling unmanned aerial vehicle and automated guided vehicle operations in an indoor manufacturing environment using differential evolution-fused particle swarm optimization,” Int. J. Adv. Robot. Syst., vol. 15, no. 1, p. 172988141775414, Jan. 2018, doi: 10.1177/1729881417754145.

[8] C. W. Reynolds, “Flocks, herds and schools: A distributed behavioral model,” SIGGRAPH Comput Graph, vol. 21, no. 4, pp. 25–34, Aug. 1987, doi: 10.1145/37402.37406.

[9] J. Kennedy and R. Eberhart, “Particle swarm optimization,” in Proceedings of ICNN’95 - International Conference on Neural Networks, Perth, WA, Australia: IEEE, 1995, pp. 1942–1948. doi: 10.1109/ICNN.1995.488968.

[10] C. J. A. Bastos-Filho and P. B. C. Miranda, “Multi-Objective Particle Swarm Optimization using speciation,” in 2011 IEEE Symposium on Swarm Intelligence, Paris, France: IEEE, Apr. 2011, pp. 1–6. doi: 10.1109/SIS.2011.5952572.

[11] M. Al-Obaidy and R. Al-Azawi, “Cluster-based Algorithm for Energy Optimization of Swarmed Robots using Swarm Intelligence,” in 2019 Sixth HCT Information Technology Trends (ITT), Ras Al Khaimah, United Arab Emirates: IEEE, Nov. 2019, pp. 202–207. doi: 10.1109/ITT48889.2019.9075119.

[12] C. Deng, “Distributed Resilient Control for Cyber-Physical Systems under Denial-of-Service Attacks,” in 2019 23rd International Conference on Mechatronics Technology (ICMT), SALERNO, Italy: IEEE, Oct. 2019, pp. 1–5. doi: 10.1109/ICMECT.2019.8932108.

[13] R. Chen, N. Xu, Y. Huang, Y. Chen, and J. Li, “Decentralized Learning Control for Multi-UAV Swarm Simultaneous Coverage and Tracking,” in Proceedings of 2021 5th Chinese Conference on Swarm Intelligence and Cooperative Control, vol. 934, Z. Ren, M. Wang, and Y. Hua, Eds., in Lecture Notes in Electrical Engineering, vol. 934. , Singapore: Springer Nature Singapore, 2023, pp. 1705–1715. doi: 10.1007/978-981-19-3998-3_159.

[14] S. Mirjalili, S. M. Mirjalili, and A. Lewis, “Grey Wolf Optimizer,” Adv. Eng. Softw., vol. 69, pp. 46–61, Mar. 2014, doi: 10.1016/j.advengsoft.2013.12.007.

[15] S. Li, H. Chen, M. Wang, A. A. Heidari, and S. Mirjalili, “Slime mould algorithm: A new method for stochastic optimization,” Future Gener. Comput. Syst., vol. 111, pp. 300–323, Oct. 2020, doi: 10.1016/j.future.2020.03.055.

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SIMULTANEOUS LIGHTWAVE INFORMATION AND POWER TRANSFER FOR NON-TERRESTRIAL NETWORKS ENABLED SITUATIONAL AWARENESS

P. D. Diamantoulakis[1], S. A. Tegos[1], G. K. Karagiannidis[1], L. Athanasekos[2] and D. Nodaros[2]

Abstract

This paper presents an innovative approach to enhancing future public-safety capabilities by integrating simultaneous lightwave information and power transfer (SLIPT) into non-terrestrial networks for situational awareness. The shift from reliance on human observers to the use of unmanned aerial vehicles (UAVs) and CubeSats is highlighted for efficient, secure, and precise intervention. Utilizing optical wireless communication, which provides secure, high-bandwidth communication free of radio frequency pollution, we explore the concept of SLIPT, which facilitates both data transmission and energy harvesting, propose a dual-purpose system architecture for UAVs, and outline strategies for overcoming the space challenges faced by CubeSats. Finally, we discuss technical challenges related to tracking accuracy, resource allocation, and receiver weight.

Keywords

Simultaneous lightwave information and power transfer (SLIPT), Unmanned aerial vehicles (UAVs), Satellites

1. INTRODUCTION

Situational awareness is a cornerstone of military efficacy, serving as the bedrock upon which strategic decisions and tactical responses are built. In the complex theatre of operations, it encompasses the continuous, real-time acquisition, analysis, and synthesis of environmental and situational data to understand the current context and predict future states. This awareness is critical across all levels of command, from individual soldiers on the ground to high-level strategic planners. Advances in technology, including satellite surveillance, unmanned aerial vehicles (UAVs), and sophisticated communication networks, have significantly enhanced the ability of armed forces to gain a comprehensive view of the battlefield. Such technologies facilitate the detection of threats, the identification of opportunities, and the coordination of movements with unparalleled precision and speed. Moreover, situational awareness extends beyond the immediate physical environment to include cyber and electromagnetic spaces, where modern conflicts increasingly unfold. By integrating information from these diverse domains, military forces can maintain a decisive advantage, adapting to dynamic conditions and outmaneuvering adversaries with informed, agile strategies.

Also, the utilization of UAVs and CubeSats has revolutionized disaster mitigation efforts, offering innovative tools for monitoring, assessment, and response strategies. UAVs provide immediate aerial imagery and data collection in real-time, enabling rapid assessment of disaster-impacted areas without risking human lives. Their agility and ability to capture detailed visual information make them invaluable for identifying accessible routes for emergency responders, assessing

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structural damage, and monitoring ongoing environmental changes. CubeSats, on the other hand, extend the capabilities of disaster mitigation from space, offering a broader perspective with continuous global monitoring. These miniature satellites can track weather patterns, environmental changes, and the progression of natural phenomena such as hurricanes, floods, and wildfires over vast areas. Together, UAVs and CubeSats form a powerful synergy for early warning systems, enhancing predictive models with precise data and significantly improving the timing and efficiency of disaster response. By integrating these advanced technologies into disaster mitigation strategies, communities and emergency management agencies can enhance their preparedness and resilience against the increasingly unpredictable challenges posed by natural disasters.

Situational awareness is a critical component of public safety operations and precise intervention, encompassing the ability to identify, process, and understand the critical elements of information about what is happening in the environment. This cognitive process enables first responders and security personnel to project and anticipate future states in emergency scenarios, facilitating informed decision-making and effective action. At its core, situational awareness is the real-time collection and analysis of environmental data, communication flows, and dynamic risk assessments. These elements are critical for orchestrating coordinated responses to emergencies, optimizing resource allocation, and minimizing the impact on affected communities. Enhancing situational awareness through technological advances and training programs can significantly improve the effectiveness of public safety operations, leading to more targeted, timely, and successful interventions in crisis situations.

The unmanned aerial vehicles (UAVs) and CubeSats represent a paradigm shift in the domain of situational awareness in public-safety applications and disaster mitigation. UAVs, with their ability to loiter and conduct surveillance over hostile territories without putting human lives at risk, offer a significant enhancement in the safety and efficacy of an intervention [1], [2]. These aerial platforms can capture real-time data on enemy movements, fortifications, and equipment, feeding this information back to command centers and artillery units with unprecedented speed and accuracy. The high-resolution imagery and thermal imaging capabilities of UAVs enable the sensing of the environment with a level of detail and precision that was previously unattainable.

On the other hand, CubeSats, which are miniature satellites launched into space, extend the capabilities for precise interventions beyond the atmospheric confines [3]. These small yet powerful tools can provide continuous surveillance over broad areas, offering strategic insights into enemy positions and movements over time. With the advantage of a bird's-eye view, CubeSats can track changes in the battlefield landscape, monitor enemy reinforcements, and predict potential threats, all from the safety of orbit. This space-based perspective not only enhances situational awareness but also contributes to the strategic planning and execution of precise intervention missions.

2. MOTIVATION AND PROBLEM STATEMENT

To meet the need for robust, secure, and efficient communication and power transfer systems for UAVs and CubeSats, the exploration of innovative technologies that overcome traditional limitations is paramount. One such promising advancement is the application of optical wireless communication (OWC), which relies on the use of light to transmit information through unguided propagation media. This approach exploits the enormous bandwidth potential inherent in optical carriers, which span the infrared (IR), visible (VL), and ultraviolet (UV) spectral regions, providing a combined bandwidth of approximately 400 THz. The use of laser or LED transmitters, known for their rapid modulation capabilities, together with receivers equipped with positive-intrinsic-negative (PIN) photodiodes or avalanche PDs (APDs), enables high-speed, linear photodetection. OWC provides several attractive features, most notably intrinsic security, as light propagation can be effectively restricted within pre-defined boundaries, eliminating the risk of eavesdropping and interference commonly associated with radio frequency (RF) technologies. In addition, OWC is immune to electromagnetic interference, supports high bandwidth and efficient bandwidth reuse, and is free of RF contamination, resulting in a cleaner spectrum and increased energy efficiency. These factors not only contribute to the operational safety and performance of UAVs and CubeSats, but also underscore the environmental benefits of reduced RF pollution.

The concept of simultaneous lightwave information and power transfer (SLIPT) is emerging as a particularly innovative application of OWC, facilitating both communication and energy harvesting through a single, streamlined process [4]. Using low-complexity passive receivers, such as non-coherent receivers and solar panels, SLIPT enables passive capture of optical signals and simultaneous power harvesting, providing a sustainable solution that minimizes energy consumption and operating costs [5]. This dual functionality overcomes the logistical and financial challenges associated with traditional power methods, such as tethering or battery swapping, by providing a wireless, autonomous power source that extends the operational range and endurance of UAVs and CubeSats without compromising their mobility or incurring significant additional costs.

In addition, the use of directional SLIPT systems provides a cost-effective, flexible means of powering UAVs via a directional optical link that not only provides significant power transfer to extend the life of the device, but also facilitates communications. This approach is particularly beneficial in optimizing the energy-to-weight ratio, a critical factor for UAVs where the goal is to maximize efficiency while minimizing additional mass. The integration of advanced solar cell technologies, such as organic and perovskite solar cells, enhances this aspect by offering superior efficiency and a favorable energy-to-weight ratio compared to traditional silicon-based cells. Its flexibility and adaptability to different surface geometries further expands the potential applications of SLIPT in UAV and CubeSat systems.

However, the practical application of SLIPT in UAV-based networks requires careful consideration of the trade-offs between energy harvesting and communication efficiency, as well as the development of appropriate theoretical channel models that accurately reflect the unique challenges posed by UAV mobility and environmental factors. Existing research underscores the importance of resource optimization and the need for comprehensive studies that take into account the dynamic operational context of UAVs, including energy consumption, mass impact, and the effects of high-power laser use. The pursuit of SLIPT for UAVs and CubeSats is therefore a multifaceted challenge that goes beyond the technical realm and requires innovative solutions that balance performance, safety, and sustainability.

3. THE FUNDAMENTALS OF SLIPT

The SLIPT concept introduces a breakthrough approach to communication and power distribution that is critical to enhancing the autonomy and functionality of unmanned aerial vehicles (UAVs) and other remote applications. At its core, SLIPT exploits the inherent directivity of light beams to minimize geometric propagation losses, enabling the efficient transfer of information and power over long distances. This characteristic is particularly beneficial in scenarios requiring long-distance point-to-point exchanges, such as underwater and airborne environments, where traditional methods fall short in terms of efficiency and reliability. Within this configuration, systems often incorporate advanced beam-alignment mechanisms to counteract potential perturbations caused by environmental factors such as wind or structural movement.

In terms of the hardware required for SLIPT, the use of resonant lasers or narrow-beam light-emitting diodes (LEDs) as transmitters plays a central role. By limiting the half-power angle of these transmitters to the milliradian range, a high degree of signal directivity is achieved, ensuring that the light beams are sufficiently focused for long-range transmission. On the receiver side, the architecture can vary to meet the specific needs of the application. An option for the receivers in a SLIPT system is a combination of photodiodes (PDs) and photovoltaic (PV) cells, tailored to efficiently receive information and convert the received optical signals into electrical energy. For PD-based information receivers, adaptive convex liquid lenses are used to precisely focus incoming light onto the active area of the PD, which can be of the positive-intrinsic-negative (PIN) or avalanche PD (APD) type, depending on the system requirements. However, the improvement of sustainability and the reduction of power consumption can be effectively achieved through the careful design and deployment of low-complexity passive receivers. In this context, noncoherent receivers come into play, especially when priorities lie in cost-effectiveness, minimal energy usage, and easy implementation on the receiver’s end. To receive noncoherent optical signals passively, a solar panel is employed as the most efficient approach for simultaneously extracting lightwave information and harvesting power. Using the solar panel, compatible with intensity modulation direct detection (IM/DD), it's possible to harvest energy from the direct current (DC) component of the modulated light, unlike the alternating current (AC) component that transmits data. This method allows for the achievement of significant data transmission rates, in the range of megabits per second (Mbps), while also generating enough energy to power various wireless devices, such as unmanned aerial vehicles UAVs and CubeSats, meeting their energy needs efficiently.

When aiming to achieve both high efficiency and low weight, it becomes essential to consider the energy produced per unit weight. Silicon crystalline solar cells, while highly efficient, do not excel in terms of energy-to-weight ratio due to their thickness. In contrast, thin-film inorganic solar cells like Copper Indium Gallium Selenide (CIGS) and a Amorphous Silicon (Si) exhibit improved specific mass, offering a better energy-to-weight ratio. However, organic solar cells and perovskite solar cells outperform the others in terms of efficiency, boasting around 10 Wg-1 and 23 Wg-1, respectively. Additionally, what sets organic and perovskite solar cells apart is their ability to be manufactured on flexible substrates. This flexibility opens up exciting possibilities for easier integration into various applications due to their adaptability to curved or irregular surfaces.

SLIPT can be realized by two main methods: The first is to use identical waveforms for both downlink data transmission and power transmission, ensuring seamless integration of communication and power. This method relies on careful waveform design to encode information while maximizing power transfer efficiency. The second approach, known as the harvest-then-transmit protocol, separates the processes in time. In this case, the system first harvests energy from the incoming lightwave, stores it, and then uses the stored energy to power the transmission of data. This method provides the flexibility to manage energy and information transfer independently, allowing adjustments based on operational requirements and availability of light resources.

4. SLIPT FOR UAVS

The advent of SLIPT technology represents a significant step forward in the capabilities of UAVs, providing an innovative dual-purpose solution for data transmission and remote power supply. This technology is unique in its ability to provide both optical data and power simultaneously, ensuring that UAVs can maintain continuous operation and secure data communications even while in motion. A key component of this architecture is the situational awareness centre. Its role is critical in receiving processed data from ground stations via a secure SLIPT method, underscoring the system's focus on maintaining operational integrity and security [6], as shown in Figure 1.

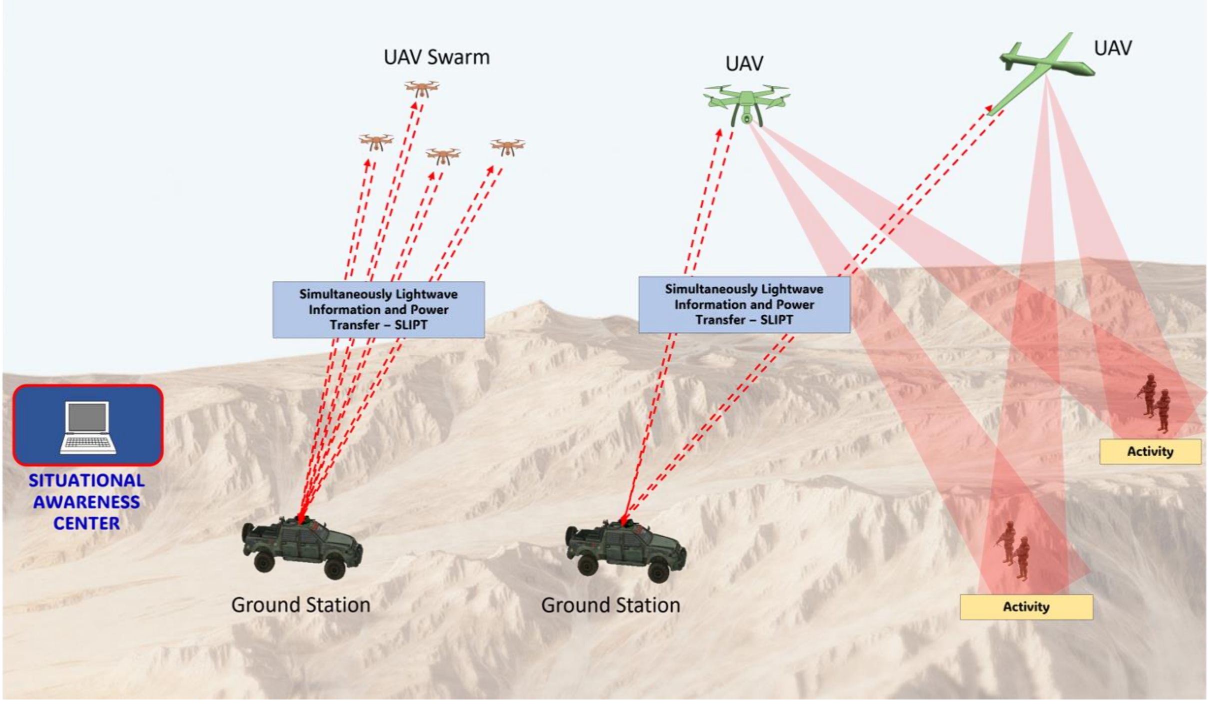

Figure 40: SLIPT for UAVs in situational awareness application.

At the heart of the proposed system is the integration of a directive SLIPT transmitter characterized by a laser array complemented by a tracking system. This system is tasked with providing the precision targeting required for effective use of the SLIPT transmitter. At the receiving end, the SLIPT receiver will incorporate solar cells along with a modified circuit designed to simultaneously process incoming information and harvest energy. This intricate design aims to significantly increase the endurance of UAVs and push the boundaries of continuous, round-the-clock operation.

Achieving the ambitious goals of this system requires overcoming several multifaceted research challenges. These include the optimal design of key components within the infrared communications (IRC) spectrum, such as lasers, solar cells, and photodiodes. A critical consideration is matching the physical dimensions of the UAV with the light collection area of the photodetector to ensure maximum efficiency in light absorption and energy conversion.

Moreover, modulating high-power lasers in SLIPT systems presents a unique set of challenges that stem from the inherent properties of high-power light sources and the physical demands of optical communication. High-power lasers can deliver the robust signal strength necessary for long-distance SLIPT links, but they require precise modulation techniques to encode data effectively without degrading the signal quality. One of the primary difficulties in modulating these lasers is managing the thermal effects associated with high-power operation. High levels of power can lead to significant heat generation within the laser diode, causing thermal lensing and changes in the refractive index, which can distort the optical beam and affect the fidelity of the transmitted signal. Additionally, the non-linear optical effects, such as self-phase modulation and stimulated Brillouin scattering, become more pronounced at higher power levels, potentially leading to signal distortion and a reduction in system performance. Implementing modulation schemes that can cope with these challenges, while maintaining high data rates and signal integrity, requires sophisticated control mechanisms and cooling strategies to mitigate thermal effects and manage non-linearities, making the modulation of high-power lasers a complex task in the development of SLIPT systems.

In addition, the system must balance the rate of data transmission with the efficiency of energy harvesting. This balance is critical and requires the formulation and application of sophisticated algorithms that take into account the energy requirements of the UAV and the desired communication bandwidth. Research and development of optical receivers capable of supporting a range of data rates, from Mbps to Gbps, is also essential. Such a diversity of capabilities will ensure that the system can meet a wide range of operational requirements, thereby increasing its applicability across different UAV platforms.

Furthermore, the comprehensive optimization and evaluation of the system architecture requires a holistic approach. This includes a thorough consideration of controllable hardware parameters and strategic deployment methodologies for SLIPT to maximize both the performance and efficiency of the system.

By addressing these challenges, the proposed system aims to revolutionize UAV operations by extending their endurance and ensuring robust and secure communication channels. The integration of SLIPT technology into UAV systems represents a forward-looking approach that promises to improve air operations and broaden the horizon for its application in various sectors.

5. SLIPT FOR CUBESATS

To address the unique challenges posed by CubeSat satellites, such as their compact dimensions and the extreme conditions of space, there is a concerted effort in the scientific community to explore and develop a number of technical strategies aimed at overcoming these obstacles and enhancing CubeSat functionality. This effort involves several critical areas of research and development, with a particular focus on advancing solar cell technologies, exploring alternative energy sources, and improving the characteristics of batteries used in space applications. The goal is to ensure that CubeSats can operate more efficiently and for longer periods of time, despite their inherent limitations [7].

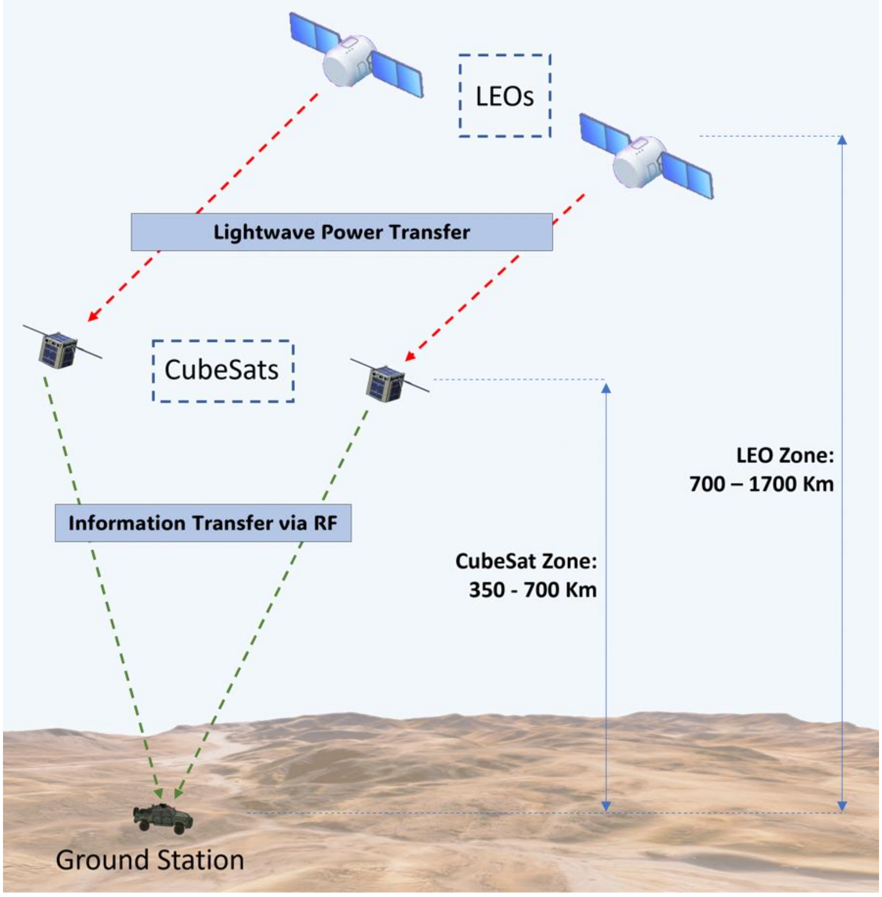

Figure 41: SLIPT for CubeSats

Another important step in optimizing CubeSat operations is the use of sophisticated energy management systems. These systems are designed to intelligently manage the energy resources available to the satellite, thereby increasing its overall efficiency and longevity. At the same time, there is an ongoing effort to develop and refine materials that have the resilience to withstand the harsh and unforgiving conditions of space. These materials must be able to withstand extreme temperatures, radiation, and the vacuum of space, making their development critical to the success of CubeSat missions.

In particular, this section focuses on the potential of SLIPT as a means of delivering power from low Earth orbit (LEO) satellites to CubeSats, achieving power delivery to the CubeSats on the order of kilowatts (kW), which is sufficient to charge their batteries [8]. This innovative approach promises not only to overcome the power limitations of CubeSats, but also to facilitate robust communication links between CubeSats and ground base stations (GBS). Preliminary results show that by using the energy delivered from LEOs, CubeSats can achieve average data rates in the order of Mbps. Establishing such links is essential for the transmission of data to Earth, allowing CubeSats to fulfil their mission objectives. The proposed system will be analysed at various intervals during the mission, allowing for a granular understanding of its operational dynamics. It is important to note that for the purposes of this analysis, the positions of both the satellites and the ground station are considered fixed during these intervals. The power derived from LEO satellites through SLIPT is specifically dedicated to communication functions, enabling the CubeSats to initiate and maintain effective communication with the GBS. This integration of wireless power transfer with data communications underscores the symbiotic nature of these processes and enhances the operational capabilities of the CubeSat.

In addition, the exploration of using satellites in higher orbits, such as medium earth orbit (MEO) and geostationary orbit (GEO), as alternative power sources open new avenues for CubeSat operations. These higher orbit satellites can potentially provide higher levels of energy that could be critical to powering CubeSats. This approach not only provides a viable solution to the energy constraints faced by CubeSats, but also expands the operational possibilities for other small satellites, particularly those used in high-demand applications. By harnessing the power of satellites in higher orbits, CubeSats could achieve greater operational efficiency and reliability, paving the way for more ambitious missions and applications in space exploration and satellite communications.

6. OPEN TECHNICAL ISSUES

SLIPT systems are at the forefront of revolutionary communication and power transfer technologies. However, their widespread adoption and integration into existing network infrastructures face several significant hurdles. These challenges span several technical and practical areas, highlighting the complexity of realizing SLIPT's full potential.

Tracking and alignment: One of the key technical issues is the precision tracking and alignment required for optimal SLIPT operation. The effectiveness of lightwave information and power transfer depends heavily on precise directional alignment between the transmitter and receiver. This requires sophisticated tracking systems capable of maintaining high accuracy in real time to counteract motion and environmental factors, which can be particularly challenging in mobile or dynamic operational scenarios such as UAVs or CubeSats in space.

Channel Modelling: Accurate statistical modelling of the channel is crucial for determining the stability needs of UAVs to sustain a specific level of link quality. This level is influenced by the requirements for communication quality-of-service and the necessary quantity of energy to be harvested when utilizing the optical wireless link for SLIPT. However, to comprehensively tackle these issues, it's essential to obtain experimental data and align the statistical parameters with the specifications of the UAVs and cubesates.

Resource allocation: Another critical issue is the efficient allocation of resources, including bandwidth and power. SLIPT systems must intelligently manage these resources to balance the dual demands of data transmission and power harvesting. This balance is critical to maximizing the efficiency and effectiveness of the transmission processes, requiring innovative solutions to optimize resource allocation under varying conditions and usage requirements.

Weight considerations: The physical characteristics of SLIPT receivers, particularly with respect to weight when airborne platforms are of interest, present a significant challenge. While it is technologically feasible to develop receivers with conversion efficiencies greater than 40%, their high cost and significant weight make them impractical for widespread mobile applications. This limitation is a barrier to the adoption of SLIPT, particularly in contexts where minimal weight is paramount. Alternatives, such as ultra-thin and lightweight film solar cells with about 20% efficiency, offer a partial solution. However, these options typically suffer from limited bandwidth, which in turn limits the data rates that can be achieved, creating a trade-off between weight and power efficiency.

Multidisciplinarity: Addressing the multiple challenges of SLIPT systems requires a multidisciplinary approach. The integration of high-speed photodetectors alongside solar cells has been proposed as a means to enhance both the energy harvesting and data transmission capabilities of SLIPT systems. While this approach aims to improve the overall performance of the system, it introduces complex issues related to the physical space allocation for both components within the receiver unit. This scenario underscores the need for innovative designs and solutions that can reconcile the requirements for high-speed data communication, efficient power transfer, and compact, lightweight construction.

7. CONCLUSIONS

The paper concludes by emphasizing the need for a collaborative, multidisciplinary effort to address the complex technical challenges of deploying SLIPT technology in public-safety applications. Highlighting the potential of SLIPT to revolutionize communications and power transfer for UAVs and CubeSats, innovative research and development is required to overcome obstacles related to tracking accuracy, resource allocation, and system architecture optimization. The integration of SLIPT into future networks is poised to significantly enhance public-safety capabilities by ensuring more secure, efficient, and sustainable operations.

References

[1] S. Berrahal, J. Kim, S. Rekhis, N. Boudriga, D. Wilkins and J. Acevedo, "Border surveillance monitoring using Quadcopter UAV-Aided Wireless Sensor Networks," Journal of Communications Software and Systems, vol. 12, no. 1, pp. 67-82, 2016.

[2] L. Tan, X. Lv, X. Lian, G Wang, “YOLOv4_Drone: UAV image target detection based on an improved YOLOv4 algorithm,” Computers & Electrical Engineering, vol. 93, 2021.

[3] K. Woellert, P. Ehrenfreund, A. J. Ricco, and H. Hertzfeld, “Cubesats: Cost-effective science and technology platforms for emerging and developing nations,” Advances in Space Research, vol. 47, no. 4, pp. 663–684, 2011.

[4] P. D. Diamantoulakis, G. K. Karagiannidis, and Z. Ding, “Simultaneous lightwave information and power transfer (SLIPT),” IEEE Transactions on Green Communications and Networking, vol. 2, no. 3, pp. 764–773, 2018.

[5] V. K. Papanikolaou, S. A. Tegos, K. W. S. Palitharathna, P. D. Diamantoulakis, H. A. Suraweera, M.-A. Khalighi, and G. K. Karagiannidis, “Simultaneous lightwave information and power transfer in 6G networks,” IEEE Communications Magazine, vol. 62, no. 3, pp. 16–22, 2024.

[6] P. D. Diamantoulakis, K. N. Pappi, Z. Ma, X. Lei, P. C. Sofotasios, and G. K. Karagiannidis, “Airborne radio access networks with simultaneous lightwave information and power transfer (SLIPT),” in IEEE Global Communications Conference (GLOBECOM), 2018, pp. 1–6.

[7] N. Saeed, A. Elzanaty, H. Almorad, H. Dahrouj, T. Y. Al-Naffouri, and M.-S. Alouini, “Cubesat communications: Recent advances and future challenges,” IEEE Communications Surveys & Tutorials, vol. 22, no. 3, pp. 1839–1862, 2020.

[8] M. Qaraqe, M. Usman, A. Serbes, I. S. Ansari, and M.-S. Alouini, “Power hotspots in space: Powering cubesats via inter-satellite optical wireless power transfer,” IEEE Internet of Things Magazine, vol. 5, no. 3, pp. 180–185, 2022.

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DUAL-USE TECHNOLOGIES AND DECENTRALIZED MANUFACTURING: AN OPPORTUNITY TO REVOLUTIONIZE EUROPEAN DEFENCE INNOVATION

R. Chandra[1] and A. Geller[2]

Abstract

This paper examines the role of dual-use technologies and decentralized manufacturing in advancing European defence innovation. It proposes a novel approach, advocating for the utilization of Europe's distinct advantages. The focus is on leveraging dual-use technologies to enhance defence capabilities. The authors argue for a transition towards decentralized manufacturing processes, such as 3D printing, for the production of defence materials. The paper underscores the importance of interdisciplinary collaboration in creating adaptable defence framework for Europe.

Keywords

Dual-Use Technologies, Decentralized Manufacturing, European Defence, Innovation, Agile Procurement, 3D Printing

1. INTRODUCTION

This call for papers challenged contributors to think outside the box. In response, this paper is to be viewed as an essay with a vision of the future, and less so as a scientific article. Rather than remaining vague, this vision has been thought through for a specific country (Switzerland) and specific technologies (dual-use) as a tangible example for how Europe could develop enhanced future defence capabilities.

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2. VISION

In an era where technological advancements unfold at an unprecedented pace and threats evolve with alarming speed, the agility to innovate and adapt is paramount for maintaining national security. Extrapolating current models of defence procurement into the future will not help us defend our freedom. This paper starts by postulating a vision (see box inset below), which will be analysed in subsequent sections.

Vision: Example of the Swiss Conscription Model Evolved for Distributed Defence Manufacturing

Traditionally, Swiss conscripts keep an assault rifle at home and regularly train in marksmanship exercises. On an annual basis, they visit 3 week refresher courses.

A potential future rendition of this model could include the production of unmanned aerial vehicles (UAVs) and other defence components using decentralized 3D printers made available to conscripts. Switzerland's conscription army, today and in the future, leverages their members' civilian professions, e.g. manufacturing, programming, and robotics. In this future scenario, conscripts receive encrypted digital blueprints for military hardware from the defence ministry for decentralized rapid production.

For select service members, regularly scheduled drone exercises replace traditional shooting drills. Conscripts become proficient at UAV-based warfighting tactics. Refresher courses help identify and overcome quality challenges of distributed production. The manufacturing process, (incl. component printing, assembly, software upload, and testing), is continuously adapted and improved as ever newer manufacturing technologies emerge.

The vision described above attempts to use rapid adaptation to shift the balance of innovation, surprise, and power to the defender. Rather than focusing on purely military technologies, European dual-use technologies are put to military use. Rather than trying to reverse engineer a smaller European version of what gives the US military its technological edge, the vision leverages European strengths. Furthermore, the vision disrupts legacy procurement processes with novel decentralized manufacturing processes and technologies.

The subsequent sections will dive deeper into each of these topics.

3. DIFFERENCES BETWEEN EUROPE AND THE US

The vision outlined above attempts to draft a unique path for Europe, capitalizing Europe's strengths and putting them to use for defence purposes rather than trying to duplicate processes used by the US. Table 1 shows significant differences between Europe and the US, impacting both regions' possibilities and means for weapons development and procurement. Instead of evaluating which structure is superior, a European strategy should embrace European idiosyncrasies and use them to its advantage. Like this Europe can become a peer-to-peer partner for the U.S. in the global contest for dominance.

Table 1: A non-exhaustive list of differences between Europe and the US that affect their ability to develop, procure and deploy high-tech weapons systems.

Europe		**US**
~30 budgets totalling €350b, fragmented procurement, fragmented R&D[10]	Centralization of procurement & R&D	€700b budget with centralized procurement, centralized R&D[11]
Minimal reliance on classification & secrecy[12]	Secrecy	Broad use of government secrecy, classification creep[12]
Professional & conscription armies with service members serving closer to their communities	Proximity of service members to their civil communities	Professional army serving far from their communities
Population wary of being perceived as militaristic or nationalistic	Attitude towards defence research & military	Predominantly patriotic population that openly supports the military endeavours
Some European nations have a strong tradition of applied education in the form of apprenticeship models, e.g. Austria, Germany, and Switzerland	Apprenticeship model	The US focuses on streamlined university education.

4. CONVERGENCE OF EMERGING DUAL-USE TECHNOLOGIES

Technological convergence is the tendency for technologies that were originally unrelated to become more closely integrated and even unified as they develop and advance[8]. To make this more tangible, Table 2 tries to illustrate how several technical developments might converge relevant to the vision described earlier. Most of the technologies in the table are dual-use in their nature, having widespread commercial applications. Yet in our vision, these technologies “converge” to deliver a significant military benefit.

Table 2: A notional selection of dual-use technologies that could converge to deliver a significant military advantage in the described vision. Europe' s largely unclassified research environment strongly benefits interdisciplinary collaboration of this kind.

Technologies:	3D printing	Advanced Materials	**Energy storage** (incl. fuels & batteries)	Robotics	**Computing** (incl quantum, AI & simulation)	Offensive & defensive Cyber & electromagnetic warfare (incl directed energy & C-UAS)
Sensors & guidance	3D printed gyroscopes for UAV position & guidance	Quantum sensing enabled by advanced materials		ISR-UAVs	Automated image processing	GPS jamming
Offensive & defensive Cyber & electromagnetic warfare (incl	3D printed antenna for Counter-UAV measures	Stealth coatings make UAV less visible to adversary	Capacitors that can deliver large energy surges for directed energy weapons	C-UAS weapons	Offensive cyber capabilities	
Computing (incl quantum, AI & simulation)	Simulations are used to rapidly convert designs to printing instructions			Autonomous UAV swarms		Command & control (C2) and doctrine
Robotics	3D printers are manufacturing robots	Lighter materials reduce energy consumption	Increase range of drones			
Energy storage (incl. fuels & batteries)	3D printed structures for batteries	Batteries using advanced materials with Higher energy density				
Advanced Materials	Advanced materials enable novel manufacturing methods					

4.1. SHIFTING THE BALANCE OF POWER TOWARD THE DEFENDER

Rapid innovation and adaptation can allow a significant rebalancing of power towards the defender. This was exemplified by tactics demonstrated by Ukraine against Russia, see box inset below. Similarly, in the initially described vision, a small European country would use rapid adaptation to increase its defensive power.

Examples of rapid technology adaptation shifting power to the Ukranian defenders[1]

- In a rapid adaptation of jet skis, mated with high explosives and advanced guidance systems, Ukraine has been neutralizing the Russian Black Sea fleet.
- Despite an acute shortage of artillery shells during the battle of Avdiivka, Ukraine was able to inflict casualty ratios of 8:1 by mass producing small drones with grenade payloads and deploying these in large numbers against massed Russian infantry

4.2. DETERRENCE THROUGH TECHNOLOGICAL PROWESS

Increasingly, we observe emerging technologies with a strong military deterrence potential. In the algebra of deterrence, nascent technologies like offensive cyber capabilities and anti-satellite technologies have started to gain mentionable status next to the classic deterrent of strategic nuclear weapons[3]. Emphasizing innovation and adaptability can complicate adversaries' planning processes and enhance strategic security. To the extent Europe continues to play a leading role in scientific research with dual-use applications, this can serve small nations to deter aggression against them, provided they have an efficient and credible process for rapidly transitioning innovation to the battlefield.

Michael Handel describes two types of technological surprise: “Type 1”, a single system that has major impact but cannot be widely employed; and “Type 2”, a large number of systems developed and widely employed[2],[9]. Type 1 surprises are rare. Examples include the Manhattan Project and Ultra, the UK’s success at breaking German Enigma encryptions in WWII. Type 2 surprises are more common. The Ukranian examples in the box above fall into this category. Although the impact of Type 2 surprizes can be assessed through simulation, the effect is to add an additional degree of complexity and therefore risk.

In conclusion, a nation that has both sufficient technological prowess, coupled with the ability to transition innovation to the battlefield, is more likely to produce Type 2, and rarely Type 1 surprizes. This can serve to deter potential aggressors.

4.3. FOSTERING COLLABORATION OF RESEARCH & MILITARY

The last paragraph of the previous subsection points out that technological prowess alone has little military value unless innovations are transitioned to actual military capability. Europe could do considerably more to leverage its technological strength for the purpose of its own military defence. To achieve this, European nations would need to foster closer collaboration between the military sector and cutting-edge research institutions. The goal is for both sides to develop working relationships and become current in addressing the challenges that come with bringing scientific discoveries to the field.

Going one step further, collaboration with military can enable testing newly developed technologies in armed conflicts. Companies like Quantum Systems and Palantir that deployed novel products in the Ukranian war effort have been able to reduce product innovation cycles from years to months [5],[6]. The opportunity is twofold – supporting a European ally while receiving rare feedback for future development.

5. RETHINKING PROCUREMENT AND MANUFACTURING

5.1. THE LIMITATIONS OF LEGACY PROCESSES

The traditional, linear models of defence procurement and manufacturing are increasingly misaligned with the dynamic needs of future warfare in an age of rapid technological innovation. The rigidity of these processes stifles the adoption of cutting-edge technologies, limiting the ability of armed forces to adapt to rapidly evolving threats, to counter adversarial technological innovations, and to adapt to rapidly changed environments (such as for example disrupted internet or other infrastructure).

The process of issuing Requests for Information (RFI), followed 6-18 months later by a Request for Proposals (RFP), increases procurement cycles to several years. The procurement of large weapons systems takes decades, see Figure 1. Similarly detrimental, forcing bidders to quote against government-determined specs is often antithetical to acquiring cutting edge capabilities.

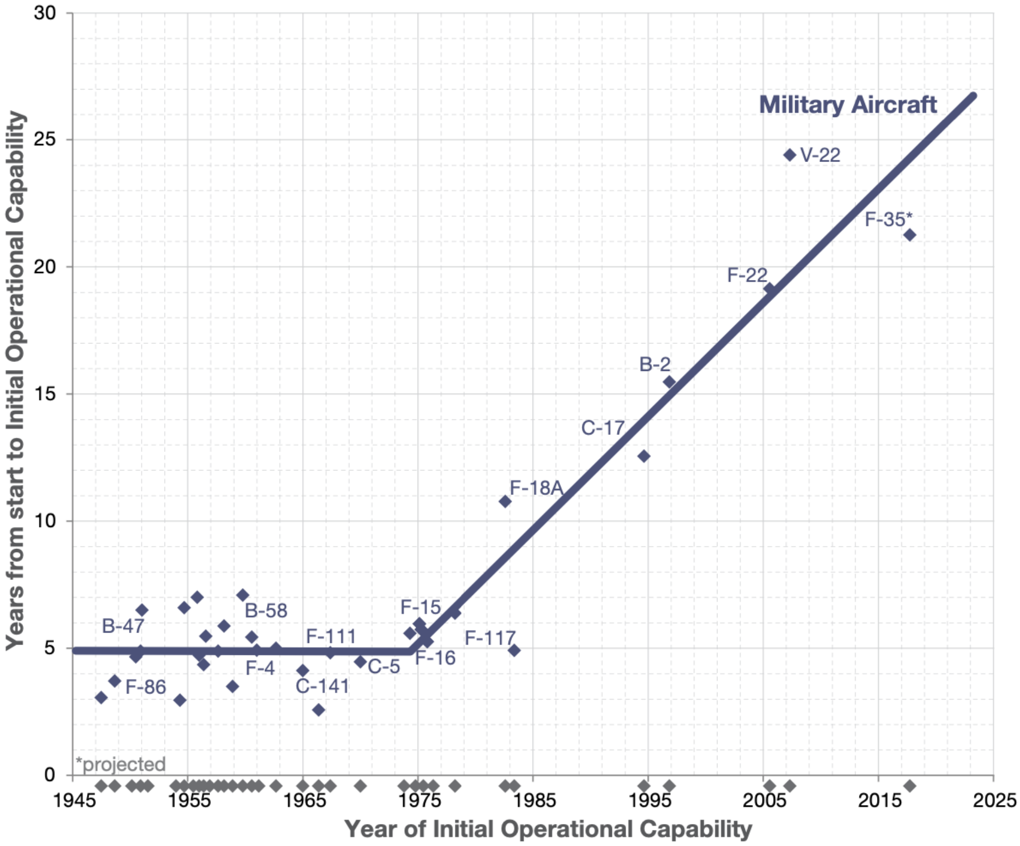

Figure 1: Current procurement processes are taking increasing amounts of time to deliver operational capabilities, as shown above for military aircraft [13].

Stronger working relationships between academia and military as suggested in Subsection “Fostering Collaboration between Research & Military” could go a long way to lubricate and accelerate the passage of scientific discovery to battlefield capability, this alone is unlikely to suffice if the legal frameworks for military procurement aren’t modified. Europe could draw inspiration from the U.S. Department of Defence's use of Other Transaction Authority (OTA) agreements. OTAs allow for faster procurement processes by bypassing traditional bidding and contracting regulations, facilitating rapid innovation and collaboration with tech startups and research institutions.

5.2. TOWARDS AGILE AND DISTRIBUTED MODELS

Radical capability increases need not solely be driven by scientific discovery. Radical acceleration of procurement cycle time can be a game-changer in its own right. Similarly, innovations in heavily-cost reduced manufacturing of weapons systems could also have a large impact on a nation's capability to defend itself.

Adopting technology-enabled procurement, manufacturing, and deployment processes (distributed manufacturing using 3D printing, and armed forces design supported by simulation in the form of large-scale socio-technical digital twins in the described vision) can revolutionize the production and deployment of military systems.

6. CONCLUSION AND RECOMMENDATIONS

In navigating the future of defence, Europe stands at a crossroads where embracing innovation and adaptability could significantly enhance its deterrence capabilities. The journey ahead requires a concerted effort to bridge the gap between cutting-edge scientific research and military application including battlefield testing when possible. This paper suggests the following list of actions to build defence mechanisms that are more robust, resilient, and responsive to the challenges of the future:

1. **It's a feature not a bug**: Europe is different from the US. Rather than viewing European idiosyncrasies as impediments to duplicating the US model, leverage the strengths of what makes us different.
2. **Embrace Dual-Use**: Over the next ten years, many commercially interesting technologies will converge to deliver capabilities of high military value. Europe's strong research community is well suited for interdisciplinary collaboration, being relatively unencumbered by official secrecy and classification.
3. **Enhance Collaboration**: Forge stronger, action-oriented partnerships between military entities and the scientific community. To the extent Europe's security or values are threatened by an ongoing armed conflict, the opportunity should be seized for battlefield testing novel systems while supporting European allies.
4. **Leverage Distributed Manufacturing to Innovate Procurement:** Adopt distributed manufacturing models, including 3D printing, to decentralize and expedite the production of defence materiel.

Like this Europe can take responsibility for its own defence, rather than being a net recipient. The US needs a sparring partner; not another follower.

References

[1] Peter Zeihan, “The New Face of Military Technology”, March 26, 2024

[2] Mark F. Cancian, “Avoiding Coping with Surprise in Great Power Conflicts”, March 23, 2024; Center for Strategic and International Studies (CSIS). Chapter 5: Technological Surprise

[3] Maria Keinonen, “Using Military Cyber operations as a Deterrent”, National Defence University, Helsinki, Finland. Proceedings of the 18th International Conference on Cyber Warfare and Security, 2023

[4] Jason Bo, “The Future of Warheads, Armour and Ballistics”, 23rd Intl. Symposium on Ballistics, April 2007

[5] Elisabeth Gosselin-Malo, “German drone maker helps Ukrainian forces own the night”, Defence News, January 23, 2024

[6] Matthew Gault & Jason Fields, “How Palantir is Using AI in Ukraine”, Angry Planet, March 26, 2024

[7] Regina E. Dugan and Kaigham J. Gabriel, ““Special Forces” Innovation: How DARPA Attacks Problems”, Harvard Business Review, October, 2013

[8] Brett Winton, “Platforms of Innovation: How Converging Technologies Should Propel a Step Change in Economic Growth”, ARK-Invest, March 21, 2024

[9] Michael Handel, “Intelligence and the Problem of Strategic Surprise,” 229–81.

[10] Lisa Jucca, “Europe defence push requires clearing M&A barriers,” Reuters, February 27, 2024.

[11] Office of the Under Secretary of Defence, “Defence Budget Overview,” March, 2023.

[12] According to Lindy Kyzer’s “How Many People Have a Security Clearance?”, Clearance Jobs, February 9, 2021, 1.3 m out of the 4.3 m cleared US citizens held a Top Secret clearance in 2019, with numbers rising at >4% annually. Numbers for Europe are difficult to obtain. It is the authors’ estimate, that Europe has less of a tendency to classify information

[13] William Greenwalt, “Competing in Time: Ensuring Capability Advantage and Mission Success through Adaptable Resource Allocation”, Hudson Institute, February 2021

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AUTONOMOUS CYBER DEFENCE AGENTS USING DRL AND LLMS TO PROTECT CRITICAL INFRASTRUCTURE NETWORKS

J. F. Loevenich[1], E. Adler[1] and R. R. F. Lopes[1]

Abstract

This study presents an architecture designed to train and evaluate robust Autonomous Cyber Defence (ACD) agents, aimed at protecting critical network infrastructure for military and civilian applications. We propose a hybrid ACD agent that integrates Deep Reinforcement Learning (DRL), Large Language Models (LLMs), and rule-based systems trained and tested against an adversarial (red) agent team to improve the robustness of the blue agent. An LLM realizes the interface between human cybersecurity experts and the AI agent leveraging recent developments in generative AI to enable continuous interaction and feedback. This interface implements Retrieval Augmented Generation (RAG) and a prompting mechanism to enrich a pre-trained LLM with information from cybersecurity knowledge graphs. The performance of the ACD agent was evaluated within a simulated NATO Protected Core Networking environment. The results suggest that both the ACD agent and the human-machine interface show great potential in enhancing the cybersecurity of critical networks.

Keywords

Cyber Security, Deep Learning, Reinforcement Learning, Large Language Model

1. INTRODUCTION

Autonomous Cyber Defence (ACD) is leveraging the rapid evolution of Artificial Intelligence (AI) technologies to ensure that our cybersecurity measures evolve at the same pace as the technological advancements of our critical systems and the increasing danger caused by automating cyber threats using AI models. Therefore, this paper introduces an innovative design for autonomous red and blue agent teams, using hybrid AI models, to protect critical network segments used for information exchange between two or more nations in a military coalition. The goal is to design and deploy autonomous agents in critical network infrastructure, using NATO standards for Protected Core Networking (PCN), improving the efficiency of cybersecurity mechanisms across coalition networks.

Recent literature suggests that hybrid AI models processing information about existing cyber threats (e.g., from threat intelligence sources like NIST, MITRE, and METASPLOIT [1,8]) can be trained to have the capability to identify unforeseen cyber threats within complex network setups [1]. Our ACD agent (blue) integrates neural and symbolic AI to combine their strength offering a more robust AI capable of logic reasoning, learning, and cognitive modelling. The ACD agent is trained using the Cyber Operations Research Gym (CybORG) environment and against two exemplary red agent strategies, where the first strategy involved sequential privileged access acquisition across subnet hosts, while the second strategy directly targeted the Operational Server, exploiting prior network layout knowledge. The human-machine interface is implemented by a pre-trained Large Language Model (LLM) (GPT-3.5-turbo-16k), which is augmented with

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cybersecurity knowledge graphs, as an external data source, using ReAct (“reasoning and acting") prompting, together with Retrieval Augmented Generation (RAG) techniques.

In short, the contributions of this paper are the following:

1. Design of a hybrid AI architecture that combines a neuro-symbolic ACD agent with cybersecurity knowledge graphs and automated red teaming designed using an LLM.
2. Evaluation of the ACD agent within an Automated Cyber Operations (ACO) gym environment, using a realistic PCN scenario.
3. Implementation and validation of a human-machine interface (ReAct+RAG) utilizing a pre-trained LLM, enabling for interaction with human cybersecurity experts.

The rest of this paper is organized as follows. Section 2. discusses related investigations, also using hybrid AI models for cyber defence. Section 3. describes the autonomous agents design and an exemplary PCN scenario. Section 4. presents results of an experimental evaluation of the ACD agent and the augmented LLM. Finally, Section 5. concludes the paper and lists future work.

2. RELATED WORK

Recent literature has introduced neuro-symbolic AI models with the potential to enhance the adaptability and performance of cybersecurity systems in the areas of intrusion detection, malware analysis, vulnerability assessment, and threat intelligence [1–3]. In a scenario characterized by the ever-changing nature of cyberattacks, the performance of AI agents depends significantly on the quantity and quality of their background knowledge. This background knowledge is used by both rule-based and Deep Reinforcement Learning (DRL) agents to create more sophisticated strategies based on real data and to tackle novel cybersecurity threats generated by the red agent teams. Thus, the knowledge graph guides the adaptive learning process of the team of defensive agents to be faster, more effective, and explainable.

LLMs have been increasingly recognized within the cybersecurity community for their potential both as tools for cyber defence [1] and for automated penetration testing [4]. In the context of automated penetration testing, LLMs demonstrate a promising capacity to simulate attacker behaviour and strategies. Recent literature suggests that they can automate "hands-on-keyboard" attacks in simulated organizational networks with varied attack tasks, endpoint configurations (Windows and Linux systems), and leverage Metasploit as the post-breach attack framework together with command-line/shell interaction [4]. Moreover, LLMs can be augmented for Question & Answer (Q/A) to incorporate external information from cybersecurity knowledge graphs using RAG [5] outperforming fine-tuned LLMs, which are costly and time-consuming [6]. For example, ReAct [7] can be enhanced with a RAG pipeline learning to answer questions about cybersecurity threats using the information from knowledge graphs built from the MITRE ATT&CK framework [1, 8].

This investigation presents an innovative methodology combining DRL, rule-based systems, and LLMs to define ACD agents protecting critical infrastructure networks. We address the challenge of integrating cybersecurity knowledge graphs into a pre-trained LLM and evaluate the performance of a human-machine interface through question-answering benchmarks. Additionally, we explore a methodology for automated red teaming, utilizing LLMs and Metasploit to improve the robustness of blue agents using an interactive feedback loop.

3. TEAMS OF AUTONOMOUS AGENTS FOR CYBER DEFENCE

3.1. AUTOMATED CYBER OPERATION GYM

The ACO gym was configured to simulate a network environment inspired by the PCN concept, as illustrated in Figure 1. This figure shows three sub-networks hosting deployable operational services within coloured clouds exposed to potential cyber threats via untrusted network infrastructures like commercial internet and satellite links (A). All network devices are implementing Software Defined Networking (SDN) interfaces, allowing for dynamic rerouting of Internet Protocol (IP) data flows to specific cybersecurity functions through virtualization or containerization (C). This capability has the computing power required for hosting the autonomous agents using hybrid AI models.

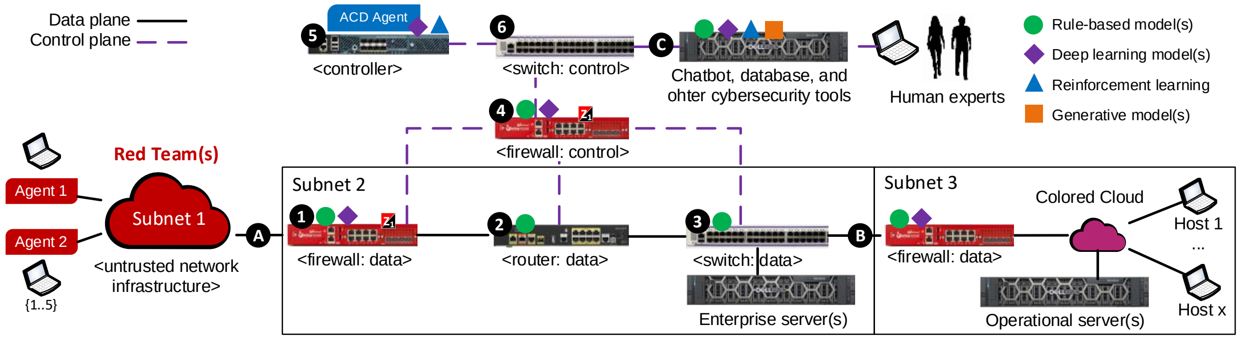


Figure 42: Network environment hosting three subnetworks, two red agents and one ACD agent [1].

The first subnet, in Figure 1, hosts five user terminals, representing the untrusted external infrastructure that could serve as entry points for cyber threats. The second subnet represents the control plane, hosting the ACD agent alongside enterprise services that support the functionalities for users in the first subnet. The third subnet, or the "coloured cloud," contains a critical operational server and three operational hosts, all of which offer various network services potentially containing exploitable vulnerabilities. Strategic firewall placements ensure that user hosts in the first subnet are restricted from directly accessing the operational server in the third subnet, which is only reachable through the operational hosts.

This simulated environment was implemented using the CybORG environment [9] to train red and blue agents. The results reported in this paper were observed during 100,000 episodes, while evaluation involves 30 to 100 episodes, each partitioned into 1000 discrete time steps. In each step, both red and ACD agents select from a high-level action set, which are then mapped to precise, context-specific low-level actions, representing the agents’ comprehensive action set.

3.2. AUTONOMOUS PENETRATION TESTING: RED AGENT

The red team is designed using an LLM for automated penetration testing integrating a Summarizer, Navigator, Planner, Experience Manager, and specialized attack tools like Metasploit, as illustrated in Figure 2 (A). The Summarizer is responsible for processing previous interactions and the execution environment, enabling the LLM to maintain context and continuity. The Planner develops the attack strategy, using the summarized information to outline the next steps. The Navigator selects the optimal action from those proposed by the Planner, considering both the immediate context and prior successful actions stored by the Experience Manager. This

Experience Manager, inspired by RAG techniques, maintains a record of past actions, facilitating the reuse of successful strategies and enhancing the efficacy of attacks. By crafting prompt templates for interaction with the LLM, the agent ensures the generation of precise attack commands, while an LLM jailbreaking technique allows for the circumvention of usage policies that typically restrict such applications.

Each episode run starts with the red agent targeting a user host in subnet 1, performing reconnaissance actions such as ’Discover Remote Systems’ and ’Discover Network Services’. This phase aims to identify new hosts/IP addresses and ascertain active services on a chosen host. Using this knowledge, the agent aims to compromise one of the network services using exploits like ‘Eternal Blue’, ‘BlueKeep’, HarakaRCE’, ‘FTP Directory Traversal’, ‘HTTPRFI’, ‘HTTPSRFI’, ‘SSH Brute Force’, or ‘SQL Injection’. Achieving ’Exploit of Network Service’ and ’Privilege Escalation’ enables access to the critical operational network in subnet 3. The ultimate goal for the red agent is to destabilize an operational service on the operational server through the ’StopService’ impact action.

This investigation tests two strategies for the red agent behaviour, namely ‘Meander’ and ‘B_line’. The ‘Meander’ agent aims to gain privileged access to all hosts in a subnet before moving on to the next one, eventually arriving at the operational server. This strategy simulates an attacker that does not know the victim’s network architecture. The ‘B_line’ agent systematically explores each subnet directly targeting the operational server using prior knowledge of the network layout. The sequence of actions during a scenario follows the order of ACD agents, user, and then red agents. After execution of the actions, the ACD agents receive an observation and a reward based on the events triggered by users and red actions.

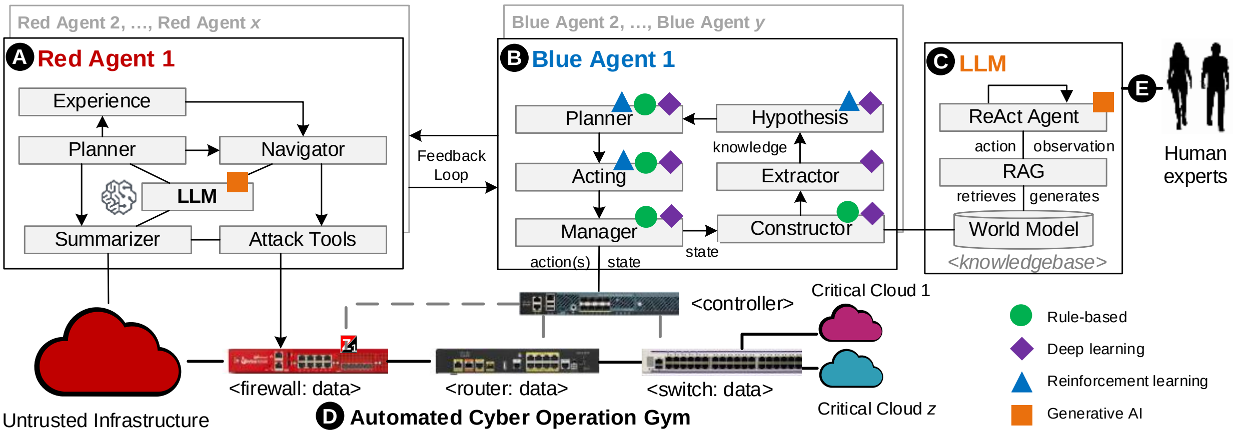


Figure 43: Red agent (A), blue agent (B), LLM (C) and gym environment (D).

3.3. AUTONOMOUS CYBER DEFENCE: BLUE AGENT

The ACD agent operates within an environment being represented by a heterogeneous knowledge graph constructed from the MITRE ATT&CK database, NIST Common Vulnerabilities and Exposures (CVEs) combined with real-time system state data. Thus, the knowledge graph augments information about cyberattack patterns, including tactics, techniques, and vulnerabilities by dynamic network information, rendering both sets of data into a structured, computable format using the Neo4j database. Nodes within this graph represent entities such as cyberattack techniques, system vulnerabilities, and network components, while edges denote the relationships between these entities, facilitating a rich, navigable data structure. The graph is continuously updated via monitoring tools that gather host-based system state information, aligning to the OpenC2 Language specifications [1], triggered by low-level actions such as

’Analyse’, ’Monitor’, ’Density Scout’, and ’SigCheck’ to enrich the graph with detailed insights into potential malware risks and compromised host services.

The agent combines rule-based, deep learning, and generative models to detect and counteract cyber threats effectively, as illustrated in Figure 2 (B). The key components are as follows: the Security Manager, sitting between the DRL model and the operational environment; the Acting Engine, which orchestrates task management and strategic planning; and the Planner, which utilizes a domain-specific operational model to navigate through potential actions using Proximal Policy Optimization (PPO) for optimal defence tactics. The World Model is defined by the heterogenous knowledge graph that encapsulates system and cybersecurity data facilitating a comprehensive understanding of the threat landscape. The Knowledge Constructor and Extractor implement Deep Neural Network (DNN) classifiers and Long Short-Term Memory (LSTM) networks to process the information from the World Model, enabling the Hypothesis Constructor to recommend informed defensive actions based on optimal policies derived from the actor-critic model.

The action space of the ACD agent is categorized into five high level actions areas, namely ’Monitor’, ’Analyse’, ’Decoy’, ’Remove’, and ’Restore’, each with specific low-level actions and intended outcomes. At the beginning of each scenario, the ACD agent is equipped with monitoring tools installed across all user and server hosts, enabling it to automatically gather knowledge about ongoing events. The ’Monitor’ action involves querying a Velociraptor Server to collect host-based state information in accordance with OpenC2 Language, yielding data on network connections and processes. For deeper analysis, the ’Analyse’ action allows the agent to perform a range of activities from calculating file density to identify potential malware with ’Density Scout’, to executing ’SigCheck’ for scanning unsigned malware files, and querying the knowledge graph for threat intelligence.

Moreover, the ACD agent can deploy a set of ’Decoy’ actions, simulating services such as ‘DecoyApache, ‘DecoyFemitter’, ‘DecoyHarakaSMPT’, ‘DecoySmss’, ‘DecoySSHD’, ‘DecoySvchost’, and ‘DecoyTomcat’. These decoys serve as honeypots to mislead the red team, providing clear indicators of hostile behavior upon access. Should a red agent attempt to exploit these decoys, the effort is automatically deemed unsuccessful, reinforcing the defence strategy. To counter the red team activities, the ACD agent can ’Remove’ red access by stopping malicious processes, an action effective only if the red agent has not yet escalated their privileges. Otherwise, the ’Restore’ action return systems to a known good state, effectively eradicating red agent activities but at the cost of disrupting user activities. It’s important to note that restoring a system from a backup is a guaranteed measure to remove red agent activity, albeit with the caveat that the red agent’s initial foothold remains present.

The observations for the ACD agent hold system information derived from either the automated execution of the ’Monitor’ function or the ’Analyse’ action. This information is compressed into a single, dense observation vector. The strategy for acting and planning within the network, is computed with an actor-critic DRL model using the PPO algorithm. The actor-critic networks include two fully connected hidden layers, utilizing ReLU activation functions for non-linear learning in the hidden layers, and a softmax activation for the final actor layer to ensure a probabilistic distribution over the action space. We allow the agent to execute a singular decoy action per host, chosen greedily from the set of available decoys for each host. Additionally, the observation vector is padded with information regarding the scanning state, identifying whether a host was previously scanned.

The agent receives a negative reward whenever the red agent gains administrator access to any system, with continuous penalties applied as long as such access is maintained. The amount of the reward depends on the host's importance to the network's security, with low importance systems having a -0.1 reward and high importance systems having a -1.0 reward. A high negative reward of -10 is received if the red agent successfully executes an 'Impact' action on the operational server. Moreover, the ACD agent pays a -1 reward for choosing the restore action on any host, reflecting the operational disruption caused by the action. Rewards are provided as a vector, categorizing the penalties into distinct dimensions (host access, server access, impact action, restore action), with the total reward being defined as the sum of these values. The final score for a blue agent is the cumulative reward received by the agent over the complete experiment.

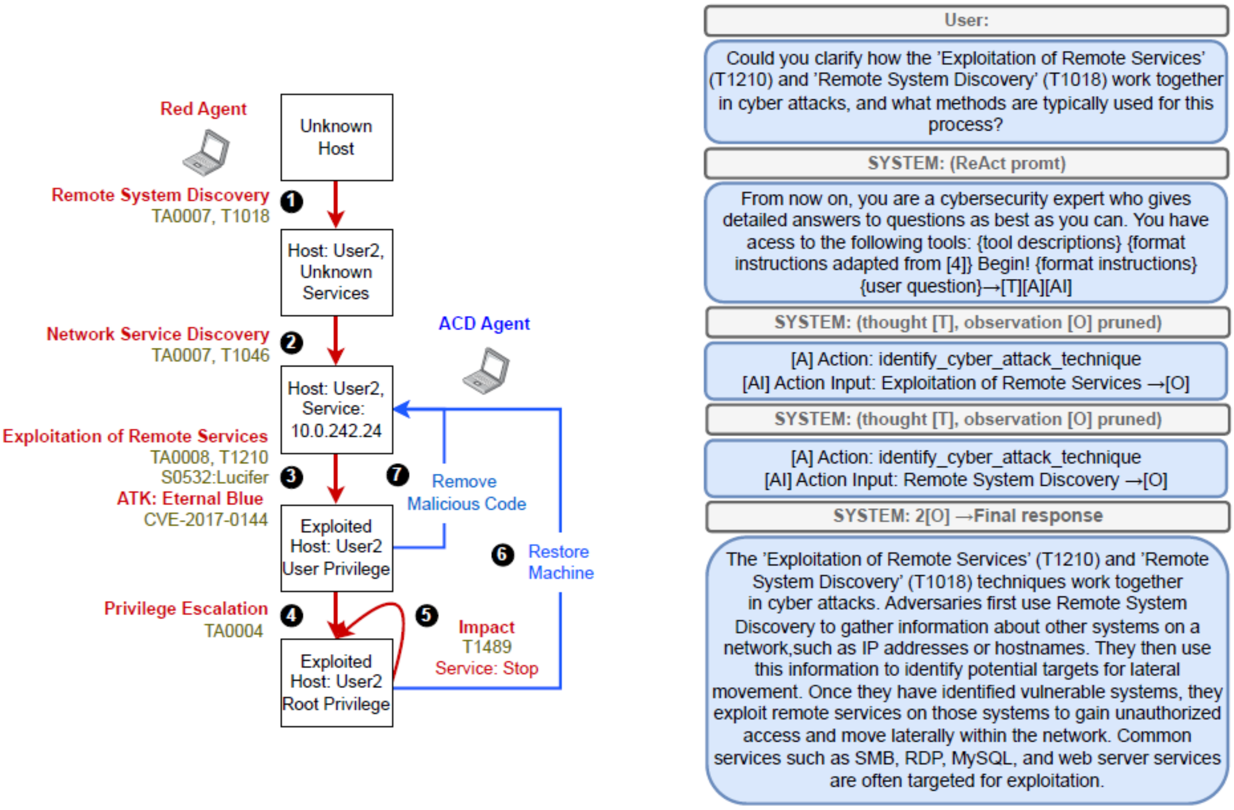
3.4. AUGMENTED LLM AS HUMAN-MACHINE INTERFACE

Our solution incorporates a pre-trained LLM as an interface for interaction with cybersecurity experts, as illustrated in Figure 2 (C). The ReAct agent integrates two retrieval methodologies: RAG search retrieval and direct retrieval, both connected to the cybersecurity knowledge graphs. This knowledgebase enables direct graph queries by the agent reducing token costs and query time.

Direct cybersecurity data retrieval is implemented by predefined Neo4j Cypher queries, where the agent is provisioned with options such as “get_group" (search for the name of a group), “get_software" (search for the name of a software), and “search_for_technique_by_id" (search for techniques by input ID). Should an input answer be insufficient for direct response, the ReAct agent is instructed to “opt" using more complex RAG-enhanced search tools. The RAG search functionalities include “identify_mitigation", “identify_cyber_attack_technique", and “identify_software". Each function requires the agent to formulate a query for the RAG mechanism to resolve. This query serves as the input for the RAG pipeline, enabling each RAG tool to be customized to address specific node types like software or mitigation requirements.

Regarding the retriever, we experimented with two embedding models. Firstly, we applied the Sentence Transformers framework generating embeddings with a reduced 384-dimensional output vector. Additionally, we applied the OpenAI embedding model, utilizing the latest iteration “text-embedding-ada-002", which supports up to 8,191 input tokens per sequence, producing a 1,536-dimensional output vector. These models facilitated the conversion of names and descriptions of node types, techniques, software, and mitigations into discrete vectors, subsequently indexed in the Neo4j vector store search index and saved within its corresponding node. The indexing is performed by the ReAct agent selecting the appropriate vector store index for querying, which in turn determines the RAG pipeline used for answering the input query.

To enhance the LLMs precision in providing updated knowledge via the RAG pipeline, it is important to prioritize nodes according their relevance to the query through the computation of minimal cosine distance among the embedding vectors and the query vector. The goal is to identify the "top_k=1" node, representing the closest semantic correlation to the query. The information from the identified node is subsequently enriched with contextual information in natural language format and synthesized by querying an LLM, with a specific prompt, to generate an answer to the query. This process includes referencing IDs of sourced documents and preserving the full context as JSON files for subsequent analysis. Finally, the answer to the query from the ReAct agent is returned as an observation and forwarded to the human expert.



User:

Could you clarify how the 'Exploitation of Remote Services' (T1210) and 'Remote System Discovery' (T1018) work together in cyber attacks, and what methods are typically used for this process?

SYSTEM: (ReAct promt)

From now on, you are a cybersecurity expert who gives detailed answers to questions as best as you can. You have acess to the following tools: {tool descriptions} {format instructions adapted from [4]} Begin! {format instructions} {user question}→[T][A][AI]

SYSTEM: (thought [T], observation [O] pruned)

[A] Action: identify_cyber_attack_technique
[AI] Action Input: Exploitation of Remote Services →[O]

SYSTEM: (thought [T], observation [O] pruned)

[A] Action: identify_cyber_attack_technique
[AI] Action Input: Remote System Discovery →[O]

SYSTEM: 2[O] →Final response

The 'Exploitation of Remote Services' (T1210) and 'Remote System Discovery' (T1018) techniques work together in cyber attacks. Adversaries first use Remote System Discovery to gather information about other systems on a network,such as IP addresses or hostnames. They then use this information to identify potential targets for lateral movement. Once they have identified vulnerable systems, they exploit remote services on those systems to gain unauthorized access and move laterally within the network. Common services such as SMB, RDP, MySQL, and web server services are often targeted for exploitation.

Ⓐ Exemplary attack scenario　　Ⓑ Exemplary human-machine interaction

Figure 44: Exemplary attack scenario (A) and human-machine interaction (B).

Figure 3 (A) shows an exemplary scenario wherein the red agent executes 'Remote System Discovery' (1) identifying the 'User2' host. Upon executing 'Network Service Discovery' (2), the agent uncovers a service at IP '10.0.242.24' that is vulnerable to the 'Eternal Blue' exploit. The agent exploits the service using Lucifer and installs malicious code to gain root access on the machine. Assuming that the ACD agent was installing decoy services on other hosts, he could now 'Remove' (7) the malicious code. If, not the red agent can proceed with 'Privilege Escalation' (4) and possibly gain root access on the 'User2' host. In this case, the only option for the ACD agent is to 'Restore' the machine (6) to a backup state. If not, the red agent can gain 'Impact' and finally stop the service.

Moreover, Figure 3 (B) shows an exemplary chat between a cybersecurity expert and the LLM. The goal is to gain deeper understanding of this attack scenario asking the LLM for specific characteristics that differentiate network service discovery from the exploitation of remote services and how they complement each other.

4. NUMERICAL RESULTS

4.1. EVALUATION OF THE AUTONOMOUS CYBER DEFENCE AGENT

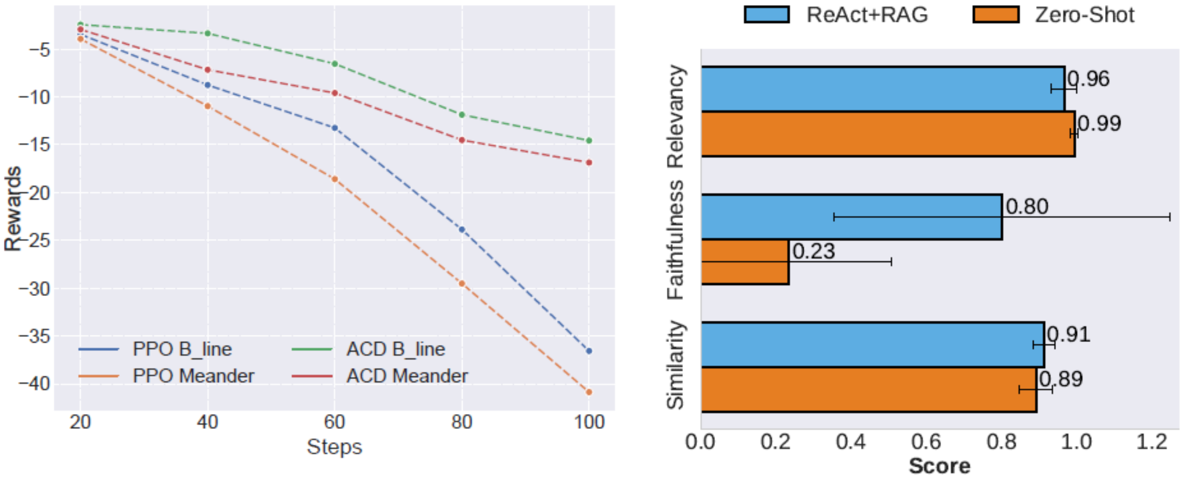
The performance of the Knowledge Extractor was evaluated using three distinct feature sets for generating node embeddings from log data. Evaluation metrics derived from applying these embeddings to classify 100,000 log samples monitored from the ACO gym environment and classified according to MITRE ATT&CK tactics, techniques, and NIST Common Vulnerabilities and Exposures (CVEs) showed accuracy rates between 98.30% and 98.37%, and F1 scores from 97.78% to 97.85% (6-12 random features used from the log data) indicating that the classifier learns to map system states to corresponding nodes within the knowledge graph.

Figure 4a presents the results from a comparative analysis of cumulative rewards between a baseline PPO Agent lacking enhancements such as host-specific decoy and decoy buffer plus scanning state integration, and our enhanced ACD agent. Both agents are tested against the two red agent strategies ‘Meander‘ and ‘B_line‘ after training of 100.000 episodes with 1000 steps each. The evaluation is done for 1000 episodes of 100 steps each, computing the cumulative reward across episodes every 20 steps. The experimental results show that the ACD agent cumulative rewards converged to about -13 for ‘B_line‘ and -16 for ’Meander’, which is a significant performance enhancement over basic PPO implementations.

Policy analysis of the ACD agent in response to ‘B_line‘ and ’Meander’ strategies revealed a consistent initial action pattern, specifically the deployment of two decoy actions, ’Fermitter User2’ and ’Tomcat User2’. The choice of a third decoy action varied based on the red agents second action. A difference in response strategies between ’Meander’ and ’B_line’ was observed at the fourth action, with ’Meander’ characterized by consecutive scans across different hosts. This observation informed the strategic decision to train ACD agents having the first three agents pre-configured to execute ’Fermitter User2’, ’Tomcat User2’, and ’SMTP Ent0’ as their initial actions.

4.2. EVALUATION OF THE AUGMENTED LLM

The dataset was derived from the Cyber Threat Intelligence (CTI)-Classification Initiative [8], consisting of adversarial techniques and unstructured sentences constructed with the MITRE ATT&CK framework’s knowledge base. The constructed graph database comprised 178 techniques, 12 tactics, 43 mitigations, 138 threat groups, and 717 software nodes for testing the human-machine interface. To enrich the dataset with relevant queries, questions were generated using ChatGPT’s GPT-4 (knowledge cut-off April 2023), each designed to correspond to a specific sentence from the CTI report within the dataset. Verification of each question ensured logical consistency with the answers, ensuring data quality and relevance for our analysis.



(a) Rewards for PPO and the ACD Agent compared against both red agents strategies *B_line* and *Meander*.

(b) Generation Results: ReAct+RAG against Zero-Shot.

Figure 45: Results for the ACD agent (a) and LLM (b) [1].

To evaluate the performance of our RAG framework we performed an independent and combined analysis of both the Retrieval and Generation components using Ragas (version 0.0.22) [10]. The analysis, plotted in Figure 4b, compares the ReAct+RAG agent to a Zero-Shot baseline (LLM without augmentation) in terms of relevancy, faithfulness, and semantic similarity. For the ROUGE-1 score, the constructed sentences of the Zero-Shot approach show a semantic similarity to the ones generated by the ReAct+RAG agent. But, analysing the ROGUE-1 and faithfulness score, we conclude that even if the generated text may be semantically similar, the answers of the Zero-shot agent may be out of context and factually wrong. We conclude that the ReAct+RAG is a better choice for producing robust and contextually accurate outputs.

For the retrieval component, we defined ’context precision’ and ’context recall’ as metrics evaluating the relevance and completeness of context retrieval in relation to the answered questions. We report a ’context precision’ score of 0.79, a ’context recall’ score of 1.0, and an overall F1 score of 0.88 reflecting full retrieval of all instances.

5. CONCLUSION AND FUTURE WORK

This paper introduced a novel architectural design of an Autonomous Cyber Defence Agent together with and adversary red agent and a human-machine interface using an augmented LLM. Our hybrid design combines a DRL model with LLMs augmented with cybersecurity knowledge graphs to protect critical infrastructure networks. A prototype of this design was implemented and evaluated in an ACO gym environment created to train and test autonomous agents defending systems in NATO PCN scenarios, which includes red agents able to discover and exploit vulnerabilities. Additionally, we propose a methodology to implement red agents using LLMs for automated penetration testing using tools like METASPLOIT. The information monitored by the ACD agent is classified, using a cybersecurity knowledge graph, to trigger an action to detect vulnerabilities in services in the network. Numerical results suggest that DRL and LLMs for blue and red teaming are a promising technique to train ACD agents using an interactive feedback loop. Moreover, the human-machine interface architecture (ReAct+RAG) also shows promising results in generating reliable responses to queries utilizing a cybersecurity knowledge graph.

As future work, we plan to extend both, the ACD and red agent architecture to host a team of specialized agents collaborating to defend the network against a wider range of cyberattacks. Another goal is to perform similar experiments on local LLMs, which could offer enhanced capabilities for storing sensitive enterprise security data in a military deployment. This future trajectory not only promises to improve the resilience of cybersecurity defences but also shows a future direction for a deeper understanding of the capabilities of AI in protecting digital network infrastructures against evolving cyber threats.

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References

[1] J. F. Loevenich, E. Adler, R. Mercier, A. Velazquez, and R. R. F. Lopes, “Design of an Autonomous Cyber Defence Agent using Hybrid AI models,” in International Conference on Military Communication and Information Systems (ICMCIS), 2024, pp. 1–10, to appear.

[2] A. Piplai, A. Kotal, S. Mohseni, M. Gaur, S. Mittal, and A. Joshi, “Knowledge-enhanced neurosymbolic artificial intelligence for cybersecurity and privacy,” IEEE Internet Computing, vol. 27, no. 5, pp. 43–48, 2023.

[3] M. Foley, M. Wang, Z. M, C. Hicks, and V. Mavroudis, “Inroads into autonomous network defence using explained reinforcement learning,” Conference on Applied Machine Learning in Information Security (CAMLIS), pp. 1-19, 2022.

[4] J. Xu, J. W. Stokes, G. McDonald, X. Bai, D. Marshall, S. Wang, A. Swaminathan, and Z. Li, “Autoattacker: A large language model guided system to implement automatic cyber-attacks,” arXiv, pp. 1–19, 2024.

[5] P. Lewis, E. Perez, A. Piktus, F. Petroni, V. Karpukhin, N. Goyal, H. Küttler, M. Lewis, W.-t. Yih, T. Rocktäschel, S. Riedel, and D. Kiela, “Retrieval-Augmented Generation for Knowledge-Intensive NLP Tasks,” in Advances in Neural Information Processing Systems, vol. 33, Inc., 2020, pp. 9459–9474.

[6] O. Ovadia, M. Brief, M. Mishaeli, and O. Elisha, “Fine-Tuning or Retrieval? Comparing Knowledge Injection in LLMs,” arXiv, pp.1-14, 2023.

[7] S. Yao, J. Zhao, D. Yu, N. Du, I. Shafran, K. Narasimhan, and Y. Cao, “ReAct: Synergizing Reasoning and Acting in Language Models,” in International Conference on Learning Representations (ICLR), pp. 1-33, 2023.

[8] O. Grigorescu, A. Nica, M. Dascalu, and R. Rughinis, “CVE2ATT&CK: BERT-Based Mapping of CVEs to MITRE ATT&CK Techniques,” Algorithms, vol. 15, p. 314, 08 2022.

[9] M. Standen, M. Lucas, D. Bowman, T. J. Richer, J. Kim, and D. Marriott, “CybORG: A gym for the development of autonomous cyber agents,” International Workshop on Adaptive Cyber Defence, pp. 1-7, 2021.

[10] S. Es, J. James, L. Espinosa-Anke, and S. Schockaert, “RAGAS: Automated Evaluation of Retrieval Augmented Generation,” in Procceedings of the 18th Conference of European Chapter of the Association for Computitional Linguistics: System Demonstrations, pp. 150-158, 2023.

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