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Nature-inspired solutions for aeronautics and space capabilities

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Abstract

European Union faces a complex environment with growing tensions and conflict situations. Thanks to the Common Security and Policy (CSDP), EU has become a leader in conflict prevention, peacekeeping operations and strengthening of international security, with the French armed forces in the forefront. The air domain has become a necessary area of operation to enable all their ambitioned capabilities. In that regard, to be even more efficient in aerospace some challenges must be tackled. For instance, in capability fields such as space-based information and communication service, information superiority (information management, Intelligence, Surveillance and Reconnaissance (ISR) capabilities, etc.), air superiority (air combat capability, air ISR platforms, etc.), air mobility, and cross-domain capabilities represent technical challenges that must be taken up by armed forces, as end-users, and ASD industrials (Aerospace, Defence and Security actors) as suppliers. These challenges can benefit from bio-inspired solutions in contexts of airborne use, naval air, and air-land.

For 3.8 billion years, living organisms have been adapting to their environmental constraints. “Survival of the fittest” is a biological trial-and-error process is the driver for the largest R&D laboratory worldwide. This has led Life to feature remarkable properties such as being composed of abundant chemical elements (C, H, N, O…) in multifunctional and adaptative materials synthetized by self-assembly at ambient temperature and pressure. Functions expected from aerospace technologies are being performed by structures and behaviors displayed by living organisms at all scales. For instance, a swarm of bees meet most of the goals that are expected from system of systems technologies including propulsion, sensors avionics, autonomous flight, and swarming. However, these functions are being referred to by specialists as moving nervous sensory-motor control, intelligence, and collective behavior by biologists, revealing one of the drags on the implementation of biomimetics today which is the lack of common language between engineers and biologists. On top of fulfilling these functions, they are met in a frugal, sustainable, and resilient way. These characteristics amongst other constitute specifications known as “Life’s principles” which can help facing challenges for the aerospace sector in this time of crises (climate change, biodiversity extinction, fossil fuel shortage etc.).

In this paper, we will briefly review the main key challenges that the ASD industry faces with a focus on end-users. Capability challenges and technical challenges will be discussed as well as issues brought by the environmental crisis. We will then present how biomimetics (the functional transposition of biological strategies to technical issues) is a formidable innovation approach to the aerospace field’s key challenges. Bio-inspired research projects and operating technologies will be reviewed with the capability prism of end-users from the ASD sector. This overview of relevant biological models of bio-inspired research tackles topics such as aerodynamics, data management,

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structures, or thermal engineering in response to the capability challenges of stealth, swarm technologies, system of systems etc.

Our final objective is to draw the aerospace community's attention on this emerging innovation strategy combining both a strong technical potential and a sustainable objective. This goal is the ambition of Myceco and Ceebios which are dedicated to promoting the development of biomimicry in France, as planned in the national roadmap of 2020. [1]

1. Introduction

The biomimetic approach takes advantage of the convergence for functional and environmental specifications between human technologies and living organisms, which have adapted to their environment over hundreds of millions of years in an efficient and frugal way. Reviewing and analyzing biological strategies allows designers and engineers to requestion their technical issues and to fuel their innovative concepts with ideas from the Living world, emphasizing on sustainable strategies.

This article (which is an adaptation of a previous Myceco work [2]) first presents the key challenges of the French ASD (aerospace, defence and security) sector and the relevance of looking at living beings as models to solve technical issues in order to sustain armed forces' capabilities. Then, it briefly shares methodological concepts, allowing biomimicry to be used as a problem-solving innovative method. Potentialities are illustrated through a review of examples on current biomimetic projects from startups technologies to academic research projects. Finally, limits and perspectives are discussed to underline the steps to come.

The objective of this article is to present the opportunities of bioinspiration in the context of the French ASD challenges. Without pretending to be exhaustive, we establish a synthesis of the state of the art, to inform, inspire and structure the action of ASD actors willing to use biomimicry as an innovative lever towards sustainability.

2. Key challenges for the defence and security aerospace industry

French Armed forces are some of the end-users of the ASD industry. Our world is subjecting them to ever changing conflict modalities: Asymmetrical conflicts, space militarization and the return of high intensity warfare define the context in they must be ready to operate nowadays. Strategic evolution of the defence environment is foreseen in a French MoD report [3] and major resulting challenges for the ASD actors can be summed up as such:

<u>Capacities challenges</u>
French armed forces aim to master and gain new capabilities to face upcoming threats. French Ministry of Defence specifies these strategic axis and work with the BITDS to stimulate technological innovation in these fields [4]. Those strategic capabilities include:

- Hypervelocity: Hypersonic velocity that enables precision strikes without interception by anti-air defence.
- Stealth: Camouflage features to bypass enemy ISR capabilities.
- System of systems: allowing interoperability of equipment of all domains (land, air, sea, space and cyber).
- Anti-drone defence systems: face low-cost drone threats
- Robotics and AI: improving our ISR capabilities and keeping soldiers safe

<u>Equipment's' reliability challenges</u>
High-tech features of defence equipment and digitalization have allowed improved capabilities for armed forces. But the backlash is a rising difficulty to maintain equipment operational. MRO (Maintenance, Repair, Overhaul) has recently become one of the main subjects for defence industrials [5].

<u>General environmental challenges</u>
Worldwide greenhouse gas emission has brought global warming: threat to agriculture, rising waters, climate migration etc. all of which converge to be a global security issue that will most likely imply instability in the decades to come. Several decades of scientific work have highlighted the link between fossil fuel consumption and our impact on the environment and on societal sustainability [6]. Thus, a transition to a fossil fuel-free system is one of the greatest challenges encountered by the ASD sector.

The technosphere as it stands compromises several other planetary boundaries than atmospheric CO_2 level [7][8]. Those boundaries define the limits not to cross for our planet to sustain human life.

Energy challenges

Even though global warning contribution by fossil fuel consumption could be an acceptable cost for defence equipment (compared to their expected benefit), fossil energetic resource is depleting [9]. This global energy crisis calls for at least 3 major levers:

- Energy efficiency: focusing innovation on making our machines more efficient
- Energy sobriety: identifying and acting on energy uses that we could spare
- Oil alternatives: researching and developing decarbonized vectors (such as H_2) to collect renewable energy sources.

Materials challenges

Such a resource depletion does not only concern energy resource. CRM (critical raw materials) designate “raw materials of high importance to the economy of the EU and whose supply is associated with high risk”, mostly metals. The graph below shows the composition of several *Rafale*’s sub-systems and their dependency to CRM [10][11]. Aircrafts and defence equipment face the risk of component’s shortage and mitigation of such a risk is a sustainability issue.

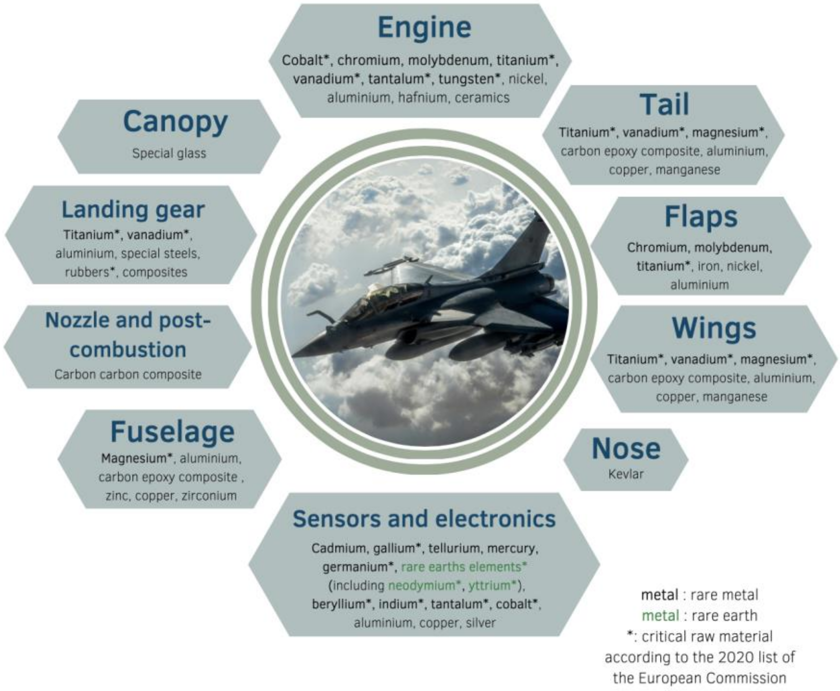

Figure 1: composition of several *Rafale*’s sub-systems and their dependency to CRM (credit: Myceco) [11]

3. Living beings as relevant examples for defence and security aerospace capabilities

Biological strategies (structures, shapes, materials, processes, organisations) are “life proven” means to achieve relevant features in domains such as mechanical resistance, energy conversion, data computing, thermal cooling, electric perception etc. in a sustainable way. Thus, there is a convergence:

- between technological capabilities needed for the ASD end-users and biological functions: camouflage, autonomy, collective intelligence, ISR etc.
- between and specifications of capabilities-enabling technologies in a sustainable world and “Life Principles” (meaning design trends and common characteristics amongst biological organisms): low energy consumption, recyclability of materials, soft conditions of temperature and pressure matter’s manufacturing, etc.

DOI: 10.13009/EUCASS2022-4706

Table 1. Biologists study embodiments of engineering domains

Engineering domains	**Biological field of studies**	**Biological model example**
Propulsion	Biomechanics and locomotion	Flapping flight
Aerodynamics		Bird’s feathers
Structures		Bird’s porous bones
Energy management	Metabolism	Lipids muscle management
Data management	Sensory et neuronal functions	Memory
Electronics		Neural transmission
Sensors		Sensory organs
Thermics	Thermoregulation	Circulatory system heat exchange

4. From an idea to a methodological process

Biomimicry relies on a methodological process which goal is to systematize the exploration of biological data when faced to a functional problem. Reviewing Life’s adaptation strategies help us unravel innovative levers and reconsider the conventional way products are designed.

Among the main steps in the development of this framework, an ISO norm defines in 2015 the various concepts related with bio-inspiration [12]:

- Biomimicry is defined as “philosophy and interdisciplinary design approaches taking Nature as a model to meet the challenges of sustainable development”.
- Biomimetics is defined as “the interdisciplinary cooperation of biology and technology or other fields of innovation with the goal of solving practical problems through the function analysis of biological systems, their abstraction into models and the transfer into and application of these models to the solution”.

This is this framework that we wish to see become an additional tool in the hand of engineers to help them break through technical barriers.

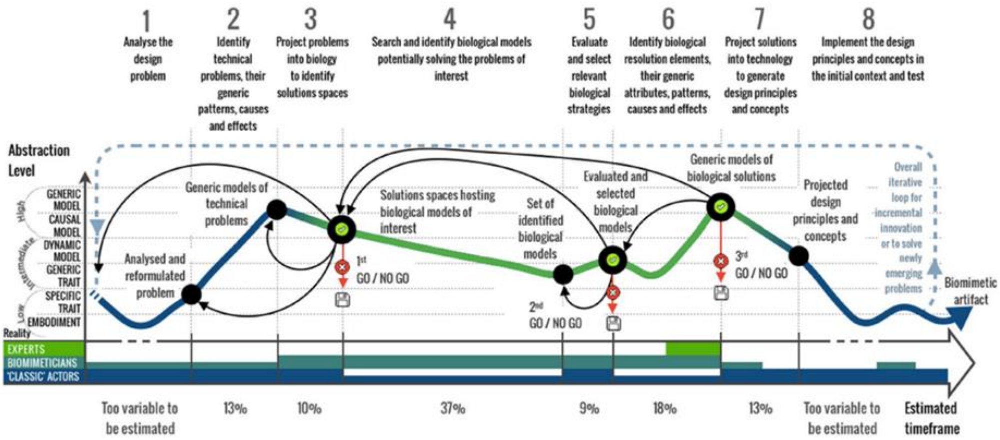

Figure 2: The Technology-Pull Interdisciplinary Biomimetic Design Process [13]

5. Examples of biomimicry potential for the defence and security aerospace industry

This section explores some projects generated from living beings’ abilities relevant in the ASD context. Reviews already explore academic contribution et research projects on specific topics [14][15]. We want to point out in that

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section the global potential that biomimicry holds and that it does not only concern innovation in the field of materials but can also give birth to diverse solutions (algorithms, organizations, processes etc.). Moreover, high TRL (Technology Readiness Level [16]) projects as well as research projects will be presented.

5.1 Materials and structures

Biological materials question the way we approach material engineering [17]. In the technological world we "heat beat and treat" to adapt a large panel of materials and atomic elements (plastics, ceramics, metals etc.) to required specifications. The biological world bets on different strategies:

- Few and locally abundant atoms used (C, H, N, O, P, S..) to assemble complex organic polymers corresponding to few molecule families (sugars, proteins, lipids, and nucleic acids).
- Biodegradable materials which can easily be disassembled and self-assembled shortly after in a soft chemistry manner.
- Complex multiscale structuration (from nano scale to macro scale) to enhance materials properties.
- Adaptative materials that change their structures and properties according to their environment.
- Materials that optimize their properties rather than maximize a sole criterion.

Table 1. Example of biomimetic potential on materials and structures

Examples of capabilities / engineering challenges	**Examples of biomimetic projects with potential**	**Ref**
Reducing weight	Light weight design	[18],[19],[20]
	Material multiscale architecture	[21]
Camouflage	Structural coloration strategy	[22]
	Cephalopod active camouflage	[23]
Aerodynamics	Drag reduction surfaces for turbines	[24]
	Aeroshark	[25]
	Biomimetic Air Vehicles	[26]
Hypervelocity	Bio inspired thermal protection system	[27]
Maintenance	Aging prediction methodologies	[28]
	Anti-icing/anti-fouling surfaces	[29]

5.2 Energy management

Living organisms must collect, store, and distribute energy. Energy usage allows them to move, perceive their environment, reproduce etc. Evolution has selected efficient strategies that allow these energy conversions in an efficient way. Moreover, Life follows some inherently sustainable strategies concerning energy that question the way we design our technologies [30]. For example:

- the biosphere runs on an energy flow (extra-terrestrial energy flow emitting from quasi-infinite stocks: the Sun) rather than on an energy stock (earth's fossil fuels stocks).
- the biosphere runs on energy carriers which are also the basic bricks for molecules with different functions (ex: glucose is an energy carrier as well as the monomer for cellulose which is a building block of plant's structural tissues)
- Organisms consume only "fresh" organic matter, which means that they emit only CO_2 that have been previously stored by photosynthesis (in accordance with a circular dynamic).

Table 2. Example of biomimetic potential on energy collection (adapted from [31])

Examples of capabilities / engineering challenges	**Examples of biomimetic potential projects**	**Ref**
Energy efficient flight	Airbus' Fello'Fly project	[32]
Sustainable lighting	Bioluminescence-based lighting	[33]

DOI: 10.13009/EUCASS2022-4706

	Fireflies-inspired LED	[34]
	Organic solid-state lighting	[35]
Hydraulics	Silent peristaltic pumps	[36]
	Undulating membrane pumps	[37],[38]
Energy storage	Mitochondria-inspired structure	[39]
	Muscle-inspired electrode	[40]
Thermoregulation	Leaf-inspired structure	[41]
Alternative to critical metals	Metabolism-inspired electrode	[42]
	Enzyme-inspired hydrogen catalysis	[43]
	Quinone-inspired liquid battery	[44]
Li-free batteries improvement	Cell-inspired carbon shell	[45]
	Bone-inspired cathode	[46]

5.3 Sensors and data management

All biological organisms manage data. They perceive it thanks to sensory organs, they transmit it through their neural system, they store it in DNA molecules, and they compute it to adapt their behaviour to external constraints [47]. Given that we are in the digitalization paradigm and that betting on data to enhance capabilities is clearly more and more energy consuming, it may be relevant to look at the energy performance of biological organisms in this area.

Table 3. Example of biomimetic potential on sensors and data management (adapted from [31])

Examples of capabilities / engineering challenges	**Examples of biomimetic potential projects**	**Ref**
Sensors and ISR	Biomimetic sensors	[48]
	Mechanical sensor	[49]
	Chemical sensor	[50]
	Acoustic sensor	[51]
Frugal data acquisition	Neuromorphic camera	[52]
Anti-drone sensors	Panoramic and compact sensors	[53],[54]
Frugal AI	Another brain	[55]
Drone collective behaviour	Swarm intelligence algorithmic	[56]

6. Discussion

There are still some limitations to the spreading of biomimicry as a systematic tool in the design toolbox of ASD engineers. Some are specific to the ASD sector while others are inherent to the innovative nature of this approach, especially the pluridisciplinarity needed to unlock bio inspired projects.

The need for training in biomimetics: to face the practical difficulties of manipulating biological data and transferring it to technological projects, to consider biomimetics intrinsic limitations, such as historical constraints in evolution. Facing this first limitation, two Masters opened in France to train the first generation of professionals specialized in biomimetics [57],[58]. Moreover, platforms to simplify biological data exploitation by engineers, using in particular AI tools, are being developed [59].

The lack of mention of bio inspiration in innovation projects: innovation have been generated from bio inspiration for as long as humans have been observing nature. However, it does not mean that bioinspired innovations are presented as such. This is a limitation to unravel the true potential of biomicry as a systematic innovation method. For example, amongst DARPA projects, none refers to biomimicry/biomimetics/bionics whereas there are clearly some that take inspiration from nature [60].

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Defence equipment service life: typical fighter aircrafts have a service life of several decades. Despite growth potential of current equipment that partially enable incremental innovation on a given design, ASD systems' inertia is a limitation for implementing biomimicry in future designs [61].

The lack of collaborations between research and industry: Numerous technologies remain at an early stage of development and so explored by academic research teams before any industrial developments. Moreover, some technologies that could actually be developed for industrial application are not known from the industrial actors. To support research transfer and valorization through collaboration between research and industry appears as a strong lever.

The need for public and private substantial investments, for academic research to further develop biomimetic technologies, for design teams to get use to the approach, for projects to mature and reach the market. Referring to other occidental countries, Germany has invested some 200 million euros overall on bio inspired research [62] and Harvard's Wyss Institute, has received more than 400 million dollars to transpose biological strategies to disruptive technologies [63]. On that aspect, various national and regional calls for projects have been developed in France to offer a financial support to academic and companies willing to explore bioinspiration. The mutualization of means to develop common technologies also appears as an axis of great potential.

7. Conclusion

For the ASD sector, biomimicry represents a great lever to support the transition to come. Several actors of the field such as Airbus, Thales, CNES, etc. are already using biomimetic approaches for various ongoing projects. Our goal is to present two complementary approaches: on one hand, to describe the paradigm in which life has evolved and the different trends that make it inherently sustainable; on the other hand, to realize that biological strategies can constitute an inspiration reservoir for engineers and designers confronted with technical problems.

We are deeply convinced that the ASD sector is a key player in the ecological transition for at least two reasons:

- Armed forces and their industrial providers are major contributors to ecological impacts. For example, it has been shown that UK's military sector emits more GHG than dozens of individual countries [64]
- Planned ecological transition can only happen in a peaceful society and ASD actors are today the guarantors of the stability of our countries. Making their role as sustainable as possible may be a prerequisite for any orderly fashioned transition to happen.

Biomimicry could be an additional subject to work on with our German neighbors who are well versed on the topic (as mentioned above). Such a collaboration would thus be yet another step toward the construction of a sustainable European defence.

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