# Artificial Intelligence Engineering for Aerospace Applications

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***Abstract*—Artificial Intelligence (AI) has made its first steps very long time ago. Aerospace has also made its moves toward the implementation of AI-based solutions. However, it faces a huge challenge because safety issues, ultimately are related to aviation certification. The review is focused on natural intelligence to inspire the development of aerospace engineering systems. The study presented in this paper allows for a better understanding of the current situation as to AI solutions in the aviation sector, and for insights into the potential use of diverse natural intelligence to be applied to aircraft and spacecraft and their enabling systems. Concluding remarks and the way forward to widen aerospace engineering applications inspired by biological life systems are also discussed.**

***Keywords—aerospace engineering, artificial intelligence, robotics and autonomous systems, bio-inspired systems.***

## I. INTRODUCTORY BASICS

Artificial Intelligence (AI) has made its first steps very long time ago back in the antiquity although it had its real boost was during the World War 2. It has faced several challenges and has been successful by sorting out problems for its acceptation/adoption in different domains since then. Some sectors, like those developing safety-critical engineering applications, have made latter progress to incorporate AI to their solutions than others (e.g. home service robots, software applications, and self-driving cars) which produce technologies that have become part of everyday life in the society. Non-critical engineering solutions usually entail system performance that either process information at non-real time constraints or do not involve human being in the system. The latter requires safety assurance and certification process to warranty human lives are properly protected.

Aerospace has also made its moves toward the implementation of AI-based solutions in astronautics and aeronautics. However, the former has facilitated AI inspiration for the development of astronautical technology such as unmanned spacecraft and space exploration vehicles, including space robotics. On the other hand, the aeronautical sector includes more conservative activities like aviation traditionally more reluctant to adopt and incorporate AI technologies. This is in great part because of the lack of determinism of such approaches (particularly, as to behaviour) and the impact of it on safety which ultimately is related to aviation certification. Behavioural system determinism comes along with performance predictability – a non-functional quality aerospace systems must have to be safety critical.

This paper reviews inspirational foundations used to develop intelligent engineering systems for different application domains. The review is focused on that intelligence (coming from nature and human beings) to inspire the development of aerospace engineering systems. It includes a range of biological principles of life and living organisms as to structures, functionality, behaviours, and processes as the main drivers to inspire smart and knowledgeable aerospace solutions. The synopsis discusses challenges and opportunities for several astronautical and aeronautical applications, including critical issues related to certification.

The comprehensive overview discusses biological metaphors and concepts from living things such as plants and animals (including humans) as well as bacteria and fungus. The discussion involves comparison tables that includes biologically inspired approaches currently used in aerospace technologies. The tables are useful to realize the state of the art of AI in aeronautics. The study presented in this paper allows for a better understanding of the current situation as to AI solutions in the aviation sector, and for insights into the potential use of diverse natural intelligence from living things to be applied to aircraft and spacecraft as well as their enabling systems. Different types of intelligence are analysed.

The rest of the paper is organized as follows. Section II discusses biologically-inspired engineering systems as key players for this investigation. Section III presents philosophical drivers of biological inspiration for AI-based engineering systems. Section IV discusses the most relevant existing AI engineering approaches for both non-aerospace applications and aerospace applications. Section V presents a critical discussion based on approaches presented in previous section. The final section presents the conclusions and future research direction.

## II. BIOLOGICALLY-INSPIRED ENGINEERNG SYSTEMS

Modern engineering systems have gone through an inexorable evolution due to the demand of more sophisticated capabilities to cope with more ambitious goals such as the development of extreme engineering systems capable of working autonomously, e.g. self-governed rovers for space explorations. They have reached a degree of sophistication that makes researchers and practitioners not only look for effective approaches but also efficient solutions to deal with such complexity. These man-made systems can be seen in different application domains such defense, healthcare, energy, aerospace, etc.

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There is an incremental role more and more of engineering systems with very complex AI algorithms and powerful computers to carry out daily human tasks. AI-based solutions are now in the society as they have become ubiquitous in diverse application domains.

One logical and attractive inspiration to develop AI-based engineering systems are biological beings such as humans as systems are requested to replace people's activities or interact with persons on their tasked operation. However, from a physical viewpoint of the biology (physiology), there are engineering applications requiring a technological approach for which not all the human abilities fulfill the need, e.g. visual mimicry from reptiles like the chameleons that change the skin color and surface to merge themselves with the environment (camouflage) to hide their presence. From a behavioral viewpoint of the biology (psychology), other abilities like collective and coordinate swarming behavior such as those shown by flocks of bees required by some applications of drone swarms.

The above situation has made researchers and practitioners develop their solutions based on biology that includes a wider spectrum of living organisms. this has given place to so-called bio-inspired or biologically inspired engineering systems. This biological inspiration provides architectural solutions for the engineering problems by means of evolved intelligent system architectures for AI-based engineering systems. Biological intelligence is arguably related to physical biology (anatomy and physiology) and behavioral biology (psychology). The later depends on the former [1].

The biological aspects under discussion entails natural abilities related to the physical biology (structures and bodies) and behavioural biology (behaviours and mind). Topics linked to the former includes branches of the biology such as physiology and anatomy as well as biological organizations and functional mechanisms and processes, e.g. self-healing, gene mutation, and cell reproduction. Topics liked to the latter includes branches of the biology such as psychology as well as biological behaviours and their operational mechanisms and processes, e.g. precepting, reasoning, and learning. Thus, the above approach entails physical and behavioral aspects of the human beings: human body (anatomy and physiology) and human mind (psychology).

## III. Phylosophy for Biologial Inspiration

This section discusses philosophical drivers of biological inspiration for AI-based engineering systems.

### *A. Inspirations in Biology*

Biology inspires IA engineering of system architectures and control algorithms as discussed in previous section. The inspiration is based on animals as well as plants and bacteria. It also includes humans as they can be biologically categorized as warm-blooded animals. Building parts and elements (anatomy), functions and operational processes (physiology), and behavior and mental processes (psychology) of living organisms are relevant for the above engineering.

Philosophers has contributed to the perception and comprehension of processes and mechanisms in living organisms by identifying and understanding the concepts and fundamental principles that explain the functioning of organs and their inter-operation. This makes possible the projection of expected performance of individual and collective tissues [2].

Most of the biological metaphors potentially attractive for the development of engineering systems were proposed by renamed philosopher although some of them were proposed by biologist or scientists within a relevant field. They are considered biological inspirations for such developments and are classified in three main classes. The following sub-sessions discuss the above inspirations.

### *B. Anatomical Inspiration*

#### *1) Apoptosis*

Apoptosis is about self-destruction of cells as it happens in multicellular organisms [3]. It is a highly regulated process that, once started, cannot be stopped. There are two approaches for a cell to be self-destroyed: (1) intrinsic pathway, and (2) extrinsic pathway. The former occurs when a cell kills itself because of cell stress. The latter occurs when a cell kills itself when is instructed by other cell(s) to do it [4].

Apoptosis has significantly brought the attention of the research community in recent decades not only from biologists but also from other disciplines. However, main efforts in biological research are on apoptosis in humans as it means a big challenge to understand the aging of the mankind (among other biological phenomena).

#### *2) Poiesis*

Poiesis refer to the ability of the living organisms to reproduction or creation [5]. It can happen by in two forms called autopoiesis and allopoiesis. The former means self-creation and was introduced by Humberto Maturana and Francisco Varela in 1972. The latter means a process for which a living organism produces another one (than itself), e.g. typical human reproduction.

Poiesis is used as a suffix for other related term in biology called hematopoiesis to name the formation of blood cells. Hematopoieses is rather linked to allopoiesis than autopoiesis as heamatopoietic stem cells are in the medulla of the bone and rise several blood cellular components [6]. Additionally, rudiments of organs in animals or humans as well as parts of a larva are intermediate formations of biological tissue of the above beings.

#### *3) Entosis*

Entonsis was introduced by a group of scientists [7] to name the invasion of a living cell into another cytoplasm of cell [8]. It is a process though cell-in-cell structures (usually considering interactions between two cells next with each other) that can involve more than two cells at a time [9].

Cells that are trapped because of entosis are alive. They can divide themselves within the host cell which sometimes release the entotic cell. This process is interesting as entotic cells can reverse entosis. However, most of the entotic cells normally kill themselves [10] by means of apoptosis.

#### 4) Autolysis

Autolysis is about self-digestion of a cell by means of the destruction of it by its enzymes. Additionally, it could also include the digestion of enzymes by molecules of the same enzyme. This could be understood as a peer-digestion. Destruction of autolytic cells is not a regular process that happens in living organisms unless there are injures in tissues and dying tissue [11].

Autolytic debridement is a process in healing wounds to break down and liquify dead tissues so the human body can wash/carry away such tissues. Additionally, a similar concept is used in the food industry to kill yeast and breakdown its cells. The result is an autolyzed yeast used to flavoring or as flavor enhancer. In this domain, this process is called plasmolysis [12].

### C. Physiological Inspiration

This subsection discusses the main physiological inspirations for AI engineering of bio-inspired systems.

#### 1) Homeostasis

Homeostasis was first introduced by a Claude Bernard in 1849, and later coined by Walter Bradford Cannon in 1926 [13]. It is about the self-regulation provided by the living organisms to maintain stable conditions for optimal survival. The internal environment of living organisms stays in an equilibrate state whilst dealing with dynamically changing external conditions.

Homeostasis is rather related to servo control than regulatory control. In the former, the reference control signal (set point) of the control variable can be dynamically changed (adjusted) to me the requirement of the demands. Examples of human homeostasis are rate of the heartbeat and body temperature. The former is increased as the muscles of an individual usually demand more oxygen when moving from being stand, walk, and then run. That increase in the oxygen requires an increase of the heart rate. The following concepts are related to homeostasis, but they do not have the same semantics than homeostasis. Hence, they are discussed separately and most of them are compared to homeostasis to understand similarities and differences as well as they are applied.

#### 2) Homeorhesis

Homeorhesis is also a concept for dynamical systems but it is about the ability of a biological system to return to a trajectory rather than a specific state as it is in homeostasis [14]. By trajectory, the homeorhesis concept target balanced flow for biological systems (organisms) that are in a steady but also continuous process to keep themselves dynamically stable. Such a firm dynamism allows for on-the-fly stability.

Homeorhesis was initially introduced by Conrad H. Waddington in 1940. It is seen as necessary capability for evolution of living organisms [15]. The term is also used in ecology with application in the Gaia hypothesis where systems are said to be in ecological balance under the concept of homeorhesis when different forms of life can co-live in the planet by keeping death and live in equilibrium without compromising resources or extinguishing species.

#### 3) Allostasis

Allostasis is a physiological process of getting performance stability (like homeorhesis and even homeostasis) but by means of behavioral changes. It is a critical process to maintain biological viability under changing conditions [16]. The term was proposed by Sterling and Eyer in 1988 for processes that make biological systems dynamically stable while deal with responses to changes of conditions.

Allostasis is applied to changes or alterations because of levels of hormones, unbalance compensated by the autonomic nervous systems, and other biological systems/subsystems in living things. Two types of allostatic processes were proposed based on the load: (1) allostatic overload occurring when demand of energy exceeds the one supplied, and (2) allostatic overload beginning with excess of energy consumption along some social factors [17].

#### 4) Enantiostasis

Enantiostasis aims to maintain overall functionality rather than a specific state as it is in homeostasis [18]. Functionality comes from metabolic and physiological functions as response to changes in the environment that can cause loss of stability in the biological system [19].

Enantiostasis means to keep a biological system and its survival functions working while facing (usually) adverse conditions. However, it does not mean the system is able to compensate by means of antagonistic effects unbalanced situations. This is understood from the definition of the term or concept which does not specified such a compensation.

### D. Psychologial Inspiration

This subsection discusses the main psychological inspirations for AI engineering of bio-inspired systems.

#### 1) Different Perpectives for Psychology

Psychology has several focuses of study. It basically tries to understand the mental processes and social behaviors of individuals. Psychologies tries to push principles and ideals to propose different types of psychology, but this paper recaps the most relevant ones for this investigation. The are discussed as follows:

- **Biological psychology** is the most aligned with the bio-inspired AI discussed in this paper. It studies physiological and neurobiological processes that support cognitive functions and behaviours [20]. Biological psychology is also called behavioural neuroscience which has different specialties, e.g. psychologists that base their research on physiology of animals (usually rats) to study mechanisms of the neural networks, genetics, and cells for learning and memory and fear responses [21].
- **Social psychology** is important for behaviour at higher levels of domain discussed in the next subsection. It studies relationships and thinking of humans with each other. Social aspects involve beliefs as well as attitudes of people. Additionally, understanding of mental processes for socialization are considered as social cognition and cognitive psychology [22].

- **Cognitive psychology** focuses on mental process [23] relevant to bio-inspired AI such decision making. This involves global and specific mental functions. Global mental functions are consciousness, orientation, and intellection. Specific mental functions are attention, memory, emotion, perception, and thought [24]. Cognition is a mental process which is not only about acquiring knowledge but also processing the existing one and even generating/creating new ones. It also entails understanding by means of thoughts, experiences, and senses [25].

#### 2) *Domain of the Behaviour*

The behavior of living organisms provides the inspiration for the operation of AI engineering systems, e.g. natural persistence (living, evolving, and managing to survive for ages) of species can inspire resilience and self-adaptation mechanisms to be engineered persistent autonomy in the above systems. Biologically inspired system operation is classified by the scope of the behavior:

- Internal-Individual Behavior (IIB)
- External-Individual Behavior (EIB)
- Internal-Collective Behavior (ICB)
- External-Collective Behavior (ECB)

They are also linked to the type of reference architecture (as defined in a previous publication [26]) where internal-individual behavior corresponds to intra-architecture, external-individual and internal-collective behaviors correspond to inter-architecture, and external-collective behavior corresponds to supra-architecture. Hence, internal-individual behavior involves single biological structures and biological granularity levels from atom to organism. External-individual and internal-collective behaviors involve a single biological structure and its interaction with other organisms (entities), and the biological granularity level of population. External-collective behavior involves multiple biological structures, and biological granularity levels (from community to biosphere).

Internal-individual behavior deals with the internal anatomy and interior conduct of all the living organisms involving only the individual, i.e. without considering interactions between organisms. Thus, it aims to only deal with internal aspects of the living-thing operation. The biology of animals and plants are considered by this operational behavior. In particular, internal dynamics of the above biological entities. However, the remaining biology kingdoms are already being an emerging inspiration (e.g. unicellular protist Paramecium caudatum [27] proposed for physical cellular automata clusters).

External-individual and internal-collective behaviors scale the operation domain of the internal-individual behavior. It involves interfaces and interactions between living organisms, and the external operation aspects of the living-thing architectures. The biology of animals and plants are considered by this operational behavior, in particular external communications with the environment and other beings as well as the internal dynamics when biological entities work as a whole formed by individual entities.

External-collective behavior deals with the conduct, and (when applicable) the comprehensive anatomy of all the living organisms. It differs from the above three behavior types since it considers the operational interaction between living organisms that form a larger and single living entity as a whole and as a part of it. External-collective behavior is not only concerned of the internal operation aspects of the living-thing architectures (when a whole) but also of external aspects (when a collection of smaller and single entities). External-collective behavior can be seen as a holistic behavior of structures (biological paradigms) as those seen in colonies and holarchies [28].

## IV. Artificially-Intelligent Applications

This section discusses the most relevant existing AI engineering approaches.

### A. *Existing Approaches for Non-Aerospace Applications*

The existing technologies for non-aerospace applications are presented according to the biological inspiration discussed in section III.

Table I shows realization of biological inspirations in anatomy in other engineering fields.

TABLE I. Anatomy-Inspired Non-Aerospace Applications

| Approach | | | Application | |
|---|---|---|---|---|
| ***Name*** | ***Metaphor*** | ***Behavior*** | ***Capability*** | ***Platform*** |
| Apoptotic robotics [29] | Apoptosis | IIB EIB | Self-destruction | Robotic systems |
| Embodiment [30] | Allopoiesis | EIB | Production | Assembly lines |
| Synthetic biology [31] | Entosis | EIB ICB | Invasion | Artificial tissue |
| Smart material [32] | Autolysis | IIB | Self-digestion | Hydrogel |
| Autonomic Repairing concrete [33] | Self-healing | IIB EIB | Self-repairing | Building structures |
| Artificial hormone [34] | Evolutionary | EIB | Self-regulation | Adaptable robots |

Table II shows realization of biological inspirations in anatomy in other engineering fields.

TABLE II. Physiology-Inspired Non-Aerospace Applications

| Approach | | | Application | |
|---|---|---|---|---|
| ***Name*** | ***Metaphor*** | ***Behavior*** | ***Capability*** | ***Platform*** |
| Viable system model [35] | Homeostasis | IIB | Self-management | Enterprise systems |
| Artificial Endocrine System [36] | Homeostasis | IIB EIB | Self-adaptation | Adaptable robots |
| Orgarnic traffic control [37] | Enantiostasis | ECB | Self-organization | Transportation systems |
| Homeorhetic assemblies [38] | Homeorhesis | ECB | Self-organization | Industrial robots |
| Allostatic control [39] | Allostasis | ICB ECB | Self-regulation | Animal robot |
| Autonomic computing [40] | Homeostatis | EIB | Self-adaptation | IT systems |
| Organic computing [41] | Enantiostasis | EIB | Self-organization | Factory automation |

Table III shows realization of biological inspirations in anatomy in other engineering fields.

TABLE III. PSYCHOLOGY-INSPIRED NON-AEROSPACE APPLICATIONS

| **Approach** | | | **Application** | |
|---|---|---|---|---|
| ***Name*** | ***Metaphor*** | ***Behavior*** | ***Capability*** | ***Platform*** |
| Artificial endocrine system [42] | Colony | EIB ICB | Self-organization/ repairing | Robotic swarms |
| Holonic Manufacturing [43] | Holoarchy | ECB | Self-organization | Production lines |
| Artificial inmune system [44] | Agency | IIB | Self-protection | Production lines |
| Intelligent vehicle control [45] | Agency | IIB EIB ICB | Self-coordination | Maritime robots |
| Swarm intelligence [46] | Colony | IEB ECB | Self-organization | Robotic systems |

Table I, II, and III summarize approaches mainly based on biological inspirations as discussed in section III. However, there are currently many bio-inspired applications for IA engineering in different domains. One of the classic approaches (given its popularity) is intelligent agent technology [47]-[53], including IA algorithms such as those for neural networks, game theory, and other emerging technologies.

### B. Potential Applications in Aerospace Engineering

The existing technologies for aerospace applications are presented according to the biological inspiration discussed in section III. They are actually the state-of-the-art realizations of bio-inspired applications. Some of them are at early stage of development with low level of Technology Readiness Level (TRL), and other are more developed approaches with higher TRLs.

The bio-inspired aerospace applications are presented in three tables even though they are not many. The idea is not only to make evident the lack of bio-approaches based on biological metaphors or philological terms discussed in this paper but also separation (three types of inspirations as those presented in this paper) for clarity.

Table IV shows realization of biological inspirations in anatomy for aerospace engineering.

TABLE IV. ANATOMY-INSPIRED AEROSPACE APPLICATIONS

| **Approach** | | | **Application** | |
|---|---|---|---|---|
| ***Name*** | ***Metaphor*** | ***Behavior*** | ***Capability*** | ***Platform*** |
| Autonomic agents [54] | Apoptosis | IIB | Self-protection | Spacecraft |
| Apoptosis for autonomy [55] | Apoptosis | IIB | Self-destruction | Space senor web |
| Autonomic management [56] | Self-healing | IIB | Autonomic management | Spacecraft |
| Autonomic agents [57] | Autopoiesis | IIB EIB | Self-creation | Space computer systems |

Table V shows realization of biological inspirations in physiology for aerospace engineering.

TABLE V. PHYSIOLOGY-INSPIRED AEROSPACE APPLICATIONS

| **Approach** | | | **Application** | |
|---|---|---|---|---|
| ***Name*** | ***Metaphor*** | ***Behavior*** | ***Capability*** | ***Platform*** |
| Smart material [58] | Self-healing | IIB EIB | Self-repairing | Aircraft |
| Autonomic management [59] | Homeostasis | IIB | Self-management | Aircraft |
| Autonomic management [56] | Homeostasis | EIB | Autonomic management | Spacecraft |

Table VI shows realization of biological inspirations in psychology for aerospace engineering.

TABLE VI. PSYCHOLOGY-INSPIRED AEROSPACE APPLICATIONS

| **Approach** | | | **Application** | |
|---|---|---|---|---|
| ***Name*** | ***Metaphor*** | ***Behavior*** | ***Capability*** | ***Platform*** |
| Agent-base multi-layer [51] | Agency | ICB | Self-organization | UAV |
| Multi-agents [60] | Agency | ICB | Self-organization | ATM |
| Reliable autonomous control [61] | Agency | ICB | Self-organization | ATM |
| Intelligent management [62] | Agency | ICB | Self-organization | ATM |
| Behavioral architecture [63] | Agency | ICB | Self-organization | ATM |
| Ontological database [64] | Cognition | EIB | Decision-making | ATM |

## V. CRITICAL DISCUSSION

Bio-inspired AI approaches with current applications on domains that are not aerospace are presented in subsection IV.A. On the other hand, subsection IV.B shows a poor number of bio-inspired AI applications in aerospace engineering. From the picture given by both subsections, it is suggested that the aerospace community is behind in terms of AI technologies, in particular those biologically inspired ones.

Most of the known bio-inspired IA solutions for aerospace are from research projects and are still under investigation with no real realization for use or product commercialization. This makes sense as a rather conservative aerospace industry obviously prioritize safety while implementing cutting-edge technology that not necessarily involve AI.

There are some designs and methodologies for bio-inspired control of small aircraft to improve the system architecture [65]. There are also bio-inspirations for flight and bionic aerodynamics to provide an overview of aircraft inspired by flying animals [66] along with biomimetics [67]. All these approaches for aerospace are mainly focused on birds which are the natural kind of the avian class from the animal kingdom. The biological inspiration presented in this paper targets concepts from microbiology for anatomy (at the tissue and cell level), physiology (at the organ and organ system level), and psychology (at the organism level).

Anatomical inspirations for aerospace are very attractive for internal system functioning. While there are few applications involving apoptosis and one for autopoesis there are no applications entailing entosis, and autolosis. These two missing metaphors are relevant for aerospace applications where fusion (merge) and auto destruction are required, e.g. avionics reconfiguration for special missions.

Physiological inspirations for aerospace are very interesting for internal system operation. While there are few applications involving homeostasis there are no applications entailing homeorhesis, allostatis, and enantiostasis. These three missing metaphors are relevant for aerospace applications where endurance (survival) and resilience are required, e.g. aircraft/spacecraft performance for long-term air/space missions.

Psychological inspirations for aerospace are very important for internal and external system operation modes. While there are few applications involving EIBs and ICBs there are no applications entailing IIBs, and ECBs. These two missing behavioral approaches are relevant for aerospace applications where autonomous individual and collective operations of systems are required, e.g. fleet of drones and team of aerial robots.

The efforts to bring ideas and implement bio-inspired solutions from disciplines (other than aerospace) are increasingly huge. However, main limitations are the constrains due to assimilation, certification of new bio-inspired technologies. The biological inspirations discussed in this paper are promising technologies for future aerospace systems.

## VI. Remarks and Further Steps

Artificial Intelligence (AI) is nowadays a pervasive discipline in many application domains. However, industrial sectors like aerospace are still behind technological AI advances in great part because of aviation certification. A review focused on natural intelligence to inspire the development of aerospace engineering systems has been presented. The study has allowed for a better understanding of the current situation of AI solutions in the aviation sector. It has also provided insights into the potential use of diverse natural intelligence to be applied to aircraft and spacecraft as well as their enabling systems. A comprehensive overview discussing biological metaphors and concepts from living things (plants, animals, humans, bacteria, fungus, etc.) has been presented. The discussion has involved comparison tables including biologically inspired approaches currently used in aerospace technologies. These tables have been useful to realize the state of the art of AI in aeronautics. Different types of intelligence have been also analyzed.

Future work will include details of bio-inspired IA approaches for aerospace for case studies along with application scenarios to show how the above technologies presented in this paper can be applied. Further development will be on enabling computer tools to design proof-of-concepts as well as to develop computer models (including computer simulations) of bio-inspired aerospace systems.

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