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DOI
10.2514/6.2024-2814

Publication date
2024

Document Version
Final published version

Published in
Proceedings of the AIAA SCITECH 2024 Forum

Citation (APA)
Joksimović, A., Brazier, F. M., Carbonneau, X., & Vingerhoeds, R. (2024). Half a Tube&Wing: Function-to-Form Mapping Approach to Understanding Fixed-Wing Civil-Aeroplane Design Space. In *Proceedings of the AIAA SCITECH 2024 Forum* Article AIAA 2024-2814 American Institute of Aeronautics and Astronautics Inc. (AIAA). https://doi.org/10.2514/6.2024-2814

AIAA SciTech Forum
8-12 January 2024, Orlando, FL
AIAA SCITECH 2024 Forum

10.2514/6.2024-2814

Half a Tube&Wing: Function-to-Form Mapping Approach to Understanding Fixed-Wing Civil-Aeroplane Design Space

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An overwhelming abundance of innovative civil aeroplane concepts has been presented by the research community in recent decades. Their development has been motivated mainly by need for better operating energy, or in particular the fuel efficiency - the common objective variable for economic and environmental optimisation. This paper focuses on one common conceptual issue with the disruptive concepts which originates in remarkable divergence of the concept space in different directions away from the conventional Tube&Wing paradigm. As a consequence, it becomes increasingly difficult to make a meaningful comparison of any arbitrary pair of concepts by employing the conventional intuitions, definitions, or figures of merit. The objective of the paper is to elaborate a framework that could encompass the entire design space under a common conceptual umbrella. The method we employ relies on systems engineering principles of Function-to-Form mapping. Firstly, a comprehensive review of innovative concepts is provided, with emphasis on the problem of the apparent complexity of the design space arising from the conventional taxonomic intuitions. Then, the descriptive framework is presented, with relevant definitions of function, form and system architecture. First-order application of the framework to the conventional aeroplane design space implies that the Tube&Wing concept family can be represented as roughly one-to-one function-to-form mapping. By analysing the summarised pool of disruptive concepts in the same key, inference is made on existence of an extensive and continuous design space. Furthermore, and argument is presented for existence of the civil-aeroplane performance optimisation trend that aligns with parts of the design space moving away from one-to-one function-to-form mapping. In other words, parts of the design space moving towards the regions in which concepts map as many functions onto as few forms as possible. If extended to the entirety of the life cycle of the system, this framework could reveal even more possibilities for system optimisation, in line with contemporary socio-economic attempts to resolve potentially contradictory requirements and constraints of sustainable growth of the aeronautical industry.

I. Introduction

The classic conundrum in evolutionary biology dating back to the era of Charles Darwin's seminal proposals of natural selection framework to explain the astounding diversity of life on Earth, originated as a challenge to Darwin himself. The question goes as follows: *What use would an animal have for "half a wing"?* The challenge, which in the long run turned out to be somewhat naive, was picking up on a perceived contradiction that arises if natural selection postulates are accepted at face value. In particular - proposition that the evolution by natural selection is *capable of changing* one living form to a completely different one based on adaptive fitness of the evolving organism's successive generations in a given environment. The question then follows, if a flying form (organism) evolves from a purely land-dwelling form (organism), what use would any intermediary organisms have of [an intermediary form represented by] half a wing, such that it is positively selected for, and that it keeps developing into the "final form" of a fully-winged bird? [1, 2]

The above conundrum can be reduced to flawed conceptualisation of evolution in the natural world, in very great sense reinforced by the fact that we tend to categorise what is in principle a *continuous* landscape of the living world using a strictly *discrete* hierarchical taxonomic system that encapsulates the species into neat, non-overlapping categories.

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Theorists like Richard Dawkins trace this fallacy back to the deeply rooted ancient legacy of Plato's *essentialism* [3]. In the same discourse where he decisively refutes essentialist arguments of ideal forms, Dawkins presents a twofold analogy between natural evolution (mainly continuous and gradual) and artificial design (gradual or discontinuous), by resorting to aeroplane engines. On the one hand, he points out that the emergence of jet engines did not happen from piecemeal evolution of the existing dedicated *machinery* - the reciprocating engines. On the other hand, he points out that the *innovation*, as is often the case in evolution of the natural world, comes from repurposing of completely different available structures that perform better (more powerfully, more efficiently) under new environmental pressures: the gas turbine in case of aeroplane propulsion. Another landmark contribution from earlier contemporary biology was presented by D'Arcy Wentworth Thompson in his classic book on growth and form. [4] The author famously attempted to explain the vast variety of living forms observed in nature by proposing the idea of the diverse biological (geometrical) forms populate one underlying "morphospace". [5] (Fig.1, left) While somewhat simplistic, and challenged for its meager understanding of evolution by natural selection, this work remains a classic, and is carried over into the contemporary state of the art biological research such as the work conducted by Levin [6], in which Wentworth's concept of continuous morphospace is directly explored to frame the modern understanding of intelligence and creation of forms *simply* as problem solving in an endlessly large and complex space of possibilities unique and common to all forms, natural or artificial.

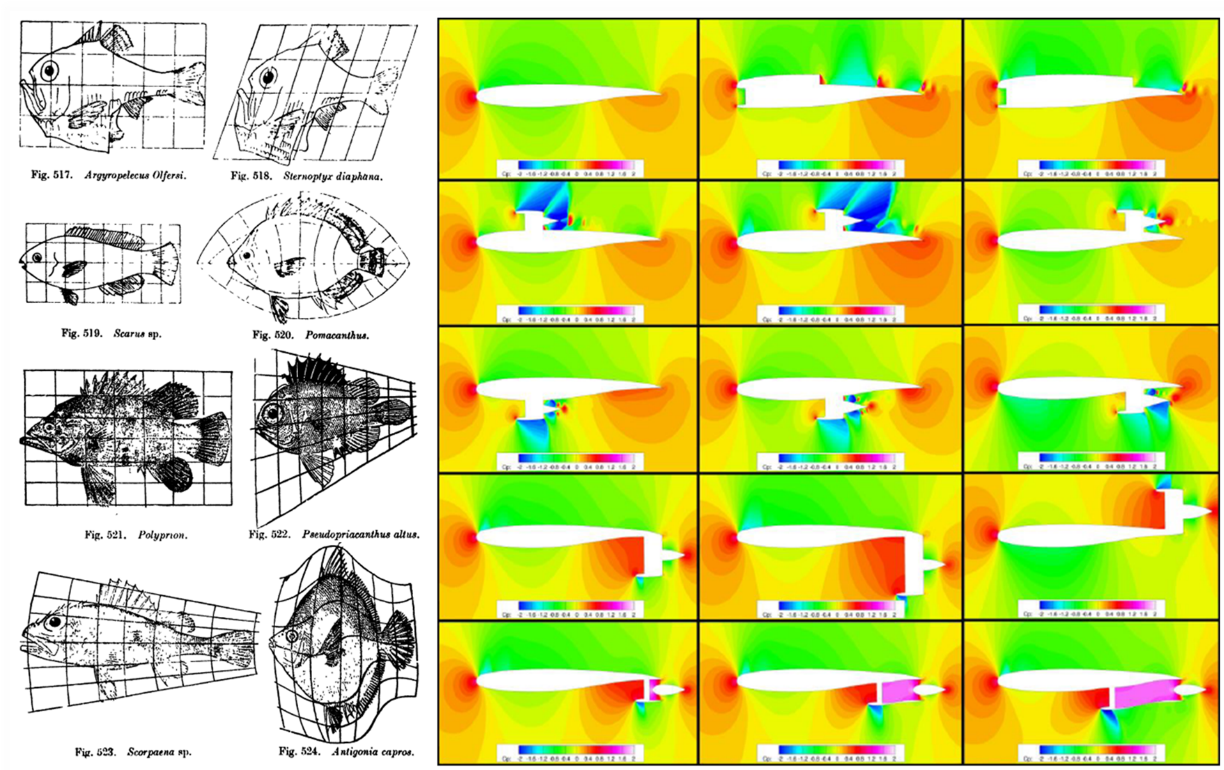

Fig. 1 Illustration of the analogy drawn between Wentworth Thompson's morphospace of the living organisms [4] (left) and theoretical possibilities for aeroplane forms, here illustrated with an excerpt of possible "integrated" aero-propulsive configurations visualised in two dimensions from work by Wick et al. [7] (right)

The interested readers are referred to authors/researchers from the aerospace domain, who took great effort to dive deeper into analogies between the aviation and the world of flying animals - even weaving some common analytical thread between the two worlds. McMasters [8] has written prolifically on energy for flight, form of flying systems and biomimetics. Bejan [9] has explored energy for flight in particular. Probably unsurprisingly, both authors follow the tradition initiated by Wenthworth Thompson's ideas, notably those on scaling laws which provide common framework to describe naturally evolved and artificial systems on the same basis.

The contemporary era witnesses the global natural world crumbling under anthropogenic pressures. In the context of the current paper in particular, impact of the aviation sector on the climate change is likely significant, especially when regarded in proportion to its size and growth ambitions. [10] For that reason, various actors across the sector have been devising new technological concepts for whole aircraft and the constituent systems, seeking to reduce or all-together remove the in-flight greenhouse gas emissions. If such objective could be attained at all, the key enabler will be development of capabilities to proverbially *get more out of less*. In particular, this concerns the material resources invested into the sector, notably matter and energy, given that both objective variables of interest: ecological impact and economic performance, fundamentally correlate to these.

Of the abundant number and variety of the presented technological concepts, most of them will not lend themselves to meaningful categorisation according to conventional taxonomies based on the so-called Tube&Wing paradigm. An example is provided in Fig.2 to illustrate challenges in attempting to describe (equivalently: to apply data and empirical models at preliminary design) innovative civil aeroplane concepts using the taxonomy based on a conventional breakdown of the vehicle according to the actors involved in its design: propulsive system, non-propulsive systems and the airframe. As the sample illustrates, different innovative airframe and non-propulsive system options could be mapped onto the conventional systems axes, but some of them could just as well be represented on either of these axes. The classical example of such dichotomy is the boundary-layer ingestion propulsion which both in its function and its form can belong to the airframe and the propulsive system categories. Taking into account the fact that the possibilities for onboard propulsive and power systems can take many different forms, all of which can theoretically synergise with the surrounding systems in many different ways - the resulting theoretical space of possibilities is something that the conventional classification cannot fully, nor coherently grasp. For a classic academic example of a conventional classification (taxonomy), see e.g. Roskam's split of aeroplane design space into 12 categories [11]; for an industry-oriented contemporary illustration, see e.g. the comparatively few categories employed by IATA in their aircraft technology roadmap to 2050. [12]

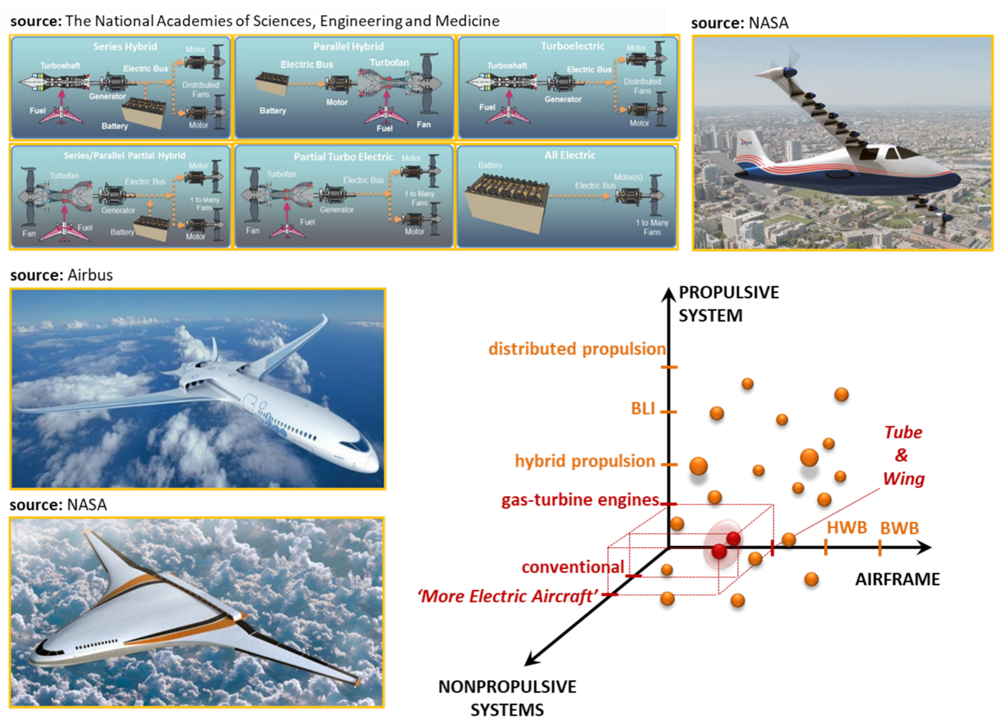

Fig. 2 Inadequacy of conventional aeroplane-system taxonomy illustrated by a small sample of airframes and hybrid-electric propulsive architectures (left). Their combinatorial possibilities alone by far outgrow the conventional Tube&Wing design space in scope and in diversity, and populate spaces that cannot be meaningfully captured using the conventional ontology.

The categorisation impasse is not a problem of book-keeping pedantry alone, but it has direct repercussions to the aeroplane preliminary sizing and design problems. Being inherently semi-empirical or empirical, the aeroplane preliminary sizing and design methods rely strongly on the underlying model data being neatly divided into correct taxonomical groups; this ensures robustness of the results on which the success of subsequent design and development depends. Succinctly, the fundamental conundrum in the preliminary sizing and design of radically different fixed-wing aeroplanes and systems lies in reconciling the nature of the design methods with the need to taxonomically determine the aeroplane design space.

This paper is inspired by a perceived analogy of the aeroplane design space with the living world. It presents arguments for existence of a theoretically continuous and extensive design space that exceeds the discrete and narrow conventional Tube&Wing-based descriptions. For a poignant, albeit still limited in the light of the possible, illustration of what this design space continuity could mean in practice, the reader is referred to the extensive parametric exploration of a distributed propulsion vehicle design space by Wick et al. [7] (Fig.1, right) The objective of the current paper is to understand and explain what seems to be theoretically vast design space by resorting to a finite set of basic principles based on the notions of *form* and *function*.

To that end, the paper continues previous work by the same authors [13]); it is organised as follows. Chapter II provides an overview of the explanatory framework used for profiling the design space analysis, with a layout of the Function-to-Form mapping formalism. Chapter III provides a review of innovative whole-vehicle and system/component concepts found in the open literature. Finally, Chapter IV takes a step back, providing a brief overview of similar trends from the historical developments, drawing an inference that aeroplane evolution can be conceptualised as continuous seek of higher function-to-form mapping, seeking more utility at the same or lower price of undesirable effects exhibited by the system in the given operating context. The position of this paper is that placing the entirety of the civil aeroplane concept *zoo* on a common explanatory ground would not only contribute to better theoretical understanding, but could serve as a basis for new preliminary architecture sizing and design methods that are largely agnostic to the architecture type, thus enabling a truly wide and versatile design space exploration and search for optimum solutions to complex problems.

II. The Formalism

A. Function and Form (FF) Framework

The current work leans on the definitions of function, form and system architecture presented by Crawley et al. [14], who state that:

- Form is the physical or informational embodiment of a system,
- Function of a system is the actions for which the system exists,
- System architecture is the embodiment of concept, the allocation of physical/informational function to the elements of form, and the definition of relationships among the elements and with the surrounding context.

Conceptually, architecture design process is simply a matter of mapping the desired system functions to a form in which the system will be materialised. The idea of function-to-form mapping serves as basis for describing the aeroplane design space based on system architectures as opposed to conventional heuristics that often mix form- and application-based notion, as e.g. *Tube&Wing*, *long-range*, *short-range*, *turbofan-* or *turboprop*-aeroplane.

B. System Coarse-Graining

In the following, definitions from the previous section are put in conjunction with a qualitative framework based on system coarse-graining. [15–17] Coarse-graining is a known concept applied in wide range of disciplines ranging from philosophy to physics (e.g. statistical mechanics). It represents breaking down of a real-world system into an arbitrary finite number of lower-level objects whose aggregate behaviour contributions add up to the total behaviour of the higher-level system being described. An illustration of coarse-graining of an *a posteriori* object can be made with a civil aeroplane. An aeroplane can be coarsely-grained into a handful of parameters that represent it simply as a material point characterised by certain mass/weight, lift, drag and thrust capabilities, as we often do in initial estimations of aeroplane performance. Then, in preliminary sizing and design we break this down further into an order of tens of parameters that now describe somewhat more intricate details such as wing surface, fuselage length, weight components, or characteristics of different stages of the mission profile. By pursuing the design and development process further, we iteratively increase the number of parameters used to describe the system, refining the granularity all the way until the system is fully developed and produced, at which point one can in principle derive any desired level of detailed knowledge from it.

This implies existence of a theoretical infinity of equivalent ways to represent a system, as many as there are possibilities to coarse-grain it. Therefore, it is simple to envision that for a very finely-grained representation of a system, a whole aeroplane in the current case, the division into subsystems consists of conceptually simple grouping of constituent objects into distinct sets. Such objects can then be represented as coarse-grained systems in their own right, and this process can repeat recursively upwards or downwards on the coarse-graining scale to represent any system at any level of detail. Fig.3 (left) presents an illustration of the described abstract concept. The granularity increase is illustrated by zooming on any individual constituent element of the successive finer- and finer-grained levels. Looking at an existing aeroplane from that perspective, the engine and the propulsive function (Fig.3, middle and right) can be seen as the lower-level constituents of the upper-level form and function, respectively. If a full picture were presented, the airframe and the non-propulsive systems would be presented next to the engine. Furthermore, next to the compressor turbines, shafts, and the engine nozzles would be presented, next to the compressor stage - every single blade of that component, as well as of the other rotating machinery, and so on. Equivalently, the aeroplane-level propulsive function, here identified with the thrust force, can be finely-grained into distinct contributions by the individual installed propulsors, whose respective individual contributions can be broken down into e.g. pressure contributions at different compressors, and then further to those of their individual blade rows, and so on.

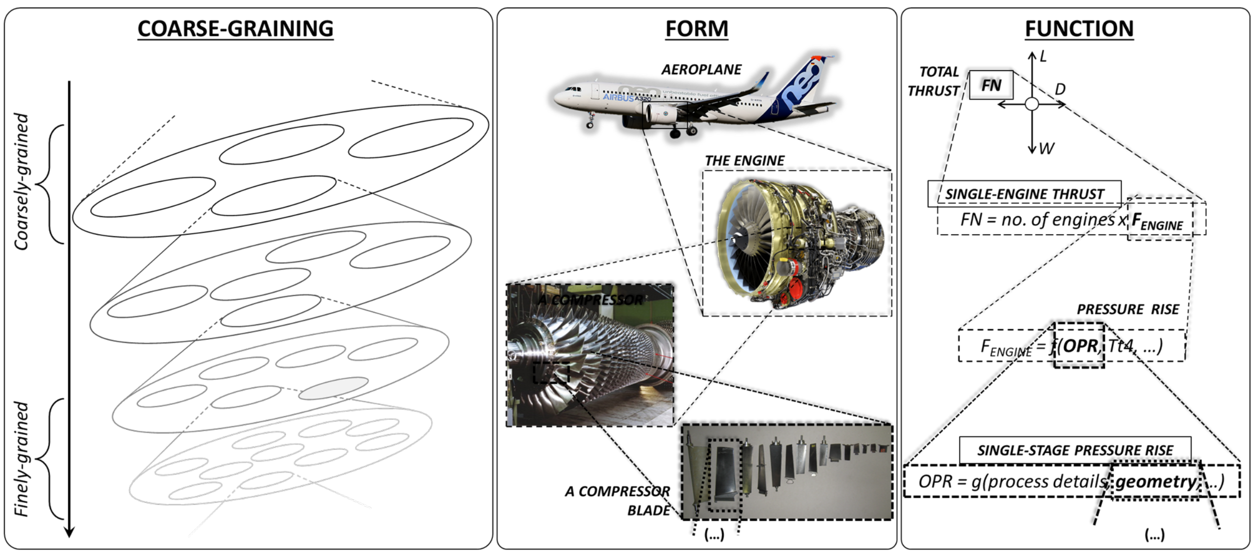

Fig. 3 Illustration of the concept of system coarse-graining into a number of increasingly finer constituent elements. (left) The illustration shows an *a posteriori* coarse-graining of a known/existing system: civil aeroplane, from the point of view of form (center) and function (right). (adapted from [17])

C. Civil Aeroplane Functions and Forms

1. Basic Functions

A complete elaboration of functions performed by an aeroplane, i.e. its functional analysis, cannot be meaningfully presented within limitations of an article, nor is it the purpose of the presented work. For the purposes of the current presentation of function-to-form mapping and innovative architecture design space survey, an elementary set of aeroplane-level in-operation features for a typical nominal flight profile is provided. The term "feature" is introduced in order to generalise the meaning that a function could assume for a system undergoing a diverse range of operating scenarios such as a civil aeroplane. Namely, to fulfil its basic mission statement of moving a useful load by air between two points on the ground, the vehicle needs to produce the necessary motive force and in turn overcome the effects that on the whole work against that action. Aeroplane needs to create lift in order to move by sustained flight, but the weight will simultaneously work against the lift. This is true of most of the operating profile, namely in all the operating scenarios where the desired direction of the movement is aligned oppositely to the weight force. Consequently, once this situation turns around, e.g. during the approach and descent mission phase, weight can be regarded as a useful contributor to the system functionality. The same is true of its effect in designing the vehicle for stability, and the same can be said of any other phenomenon that works in opposition to the functional phenomena. While no designer endeavours to maximise these effects simply because they are necessarily useful in certain regions of the operating envelope, they can be nonetheless included in the overall book-keeping of the functional features of the system.

In line with the current reasoning, the features are split into "Functional features" (what might be commonly referred to as "functions") and "Features contingent on the functions". In accordance with the conventional technological paradigm, the following high-level (or "vehicle-level") features are taken into consideration:

1) **Functional features:**
   - **Thrust:** to provide the force balance necessary for controlled flight along a desired trajectory; to overcome the inertia and the aerodynamic drag on the vehicle when necessary.
   - **Lift:** to sustain the aeroplane in level flight (to overcome weight); to provide vertical acceleration as well as the overall force balance for controlled and stable flight.
   - **Control:** to enable guiding of the vehicle in the desired direction at necessary speed.
   - **Stability:** to provide restoring forces and momenta should an unexpected perturbation of the equilibrium arise in operation.
   - **Useful volume:** for passenger/cargo storage space provision along with housing of the onboard systems.
   - **Life conditions provision:** for passenger sustenance and comfort.
   - **Structural integrity:** (self-explanatory).
   - **Ground contact:** for enabling safe contact between the vehicle on the ground.
2) **Features contingent on the functions:**
   - **Weight:** gravitational pull on massive objects.
   - **Inertia:** resistance of a body (its mass) to a change in its state of movement.
   - **Aerodynamic drag:** resistance of the fluid exerted on the body moving through it.

1) FUNCTIONAL FEATURES	Ground roll & Hor. acceleration	Climb Hor. & Vert. acceleration	Cruise, level flight	Descent Hor. & Vert. deceleration	Ground roll Hor. deceleration
Thrust:					
- To balance drag	-	-	X	-	-
- To accelerate	X	X	-	-	X
Lift:					
- To balance weight	-	-	X	-	-
- To accelerate	X	X	-	X	-
Control	X	X	X	X	X
Stability	X	X	X	X	X
Storage space	X	X	X	X	X
Life conditions/comfort	X	X	X	X	X
Structural integrity	X	X	X	X	X
Ground contact	X	-	-	-	X
2) CONTINGENT FEATURES					
Weight	X	X, X	X, X	X	X
Drag	X, X	X, X	X, X	X	X
Inertia	X, X	X, X	X, X	X, X	X, X

Fig. 4 Representative vehicle-level features, functional and contingent on function, for a typical civil aeroplane operating profile.

The described breakdown is illustrated in Fig.4; the two groups of features are contextualised at distinct operating conditions typical of a nominal civil aeroplane operating profile. The synthesis consists of two elements. Firstly, the functional features of the vehicle do not operate equally at all operating points, some of them being active at certain points, and inactive at others. Ground contact feature is evidently not necessary in flight, the same way as the thrust is not necessary during deceleration at the mission end. Secondly, the contingent features exhibit some more complicated behaviour, equally as a function of the operating condition. In the figure, red X-marks represent features working against the action of the functional features, and the green X-marks represent them being in alignment. Taking the example of the drag, nominally and primarily it is a feature that opposes the desired motion of the vehicle. This is represented with the red X-marks during the first three mission phases. In turn, the green X-mark attached to them represents the fact that the drag will serve as contributor to stabilising forces at any of these flight situations; and evidently during the phases where deceleration is important, the drag feature will exhibit unambiguous function-oriented behaviour. It is acknowledged that all the mentioned behaviours are in reality highly mutually coupled, but it makes no difference for the current development. Additionally, it can be remarked that no abnormal operating conditions were taken into consideration evidently, but the applied reasoning would apply to those just as well as to the nominal ones. The main takeaway of the presented development is that even at the most basic description level that can be applied at preliminary sizing and design, the idea of system function can be generalised beyond a simple notion of momentary in-operation utility. A repercussion of this observation is that forms can be considered to exhibit functional behaviour also if they work to counteract the contingent features in parts of the operating envelope where this could be of interest.

In line with the basic coarse-graining principles explained earlier, the above aeroplane-level features can be broken down in several ways, depending on which physical phenomena the high-level functions are identified with in the first place. Typically, the propulsive function will be identified with a propulsive force. This functional feature can be coarse-grained further into multiple force contributions, which themselves can be broken down into pressure rises, expansions or flow accelerations depending on the how the propulsive function is materialised into a form. Some typical of system-level features on an aeroplane can be:

1) **Functional features:**
    - Air/fluid compression.
    - Air/fluid transmission.
    - Heat exchange.
    - Flow acceleration.
    - Energy/power storage.
    - Energy/power transmission.
    - Useful volume provision.
    - Actuation.
    - Structural stress resistance.
2) **Features contingent on the functions:**
    - Adverse pressure gradient.
    - Heat loss.

The same process can be applied at any further coarse-graining level of interest.

2. Basic Forms

After having listed representative functions at whole-vehicle and subsystem level alike, the same can be done with representative aeroplane forms, prone to the same coarse-graining-based reasoning in their own right. Listing the forms is a somewhat more challenging exercise than listing the functions, as there are practically infinitely many possible forms for the same underlying system functions. For the sake of illustration, the representative sample of forms used in the current development is the following:

- Airframe:
    - Wing,
    - Fuselage,
    - Stabilisers,
    - Control surfaces,
    - Landing gear,
- Engine,
- Environmental control system.

It is underlined that the above breakdown of aeroplane functions and forms is restating the state-of-the-art convention representative of the Tube&Wing concept family. While it might seem paradoxical to fall back to the categorical thinking that was challenged in the outset, it is necessary to use these categories to initialise the development. Once established, it will enable to employ the framework more flexibly at a later stage, i.e. going beyond these forms to any desirable direction.

This is owing to the fact that coarse-graining formalism is impartial to the underlying ontology. That is, to represent the thrust function, one would conventionally coarse-grain it into "thrust" and "drag" objects. Control engineer will

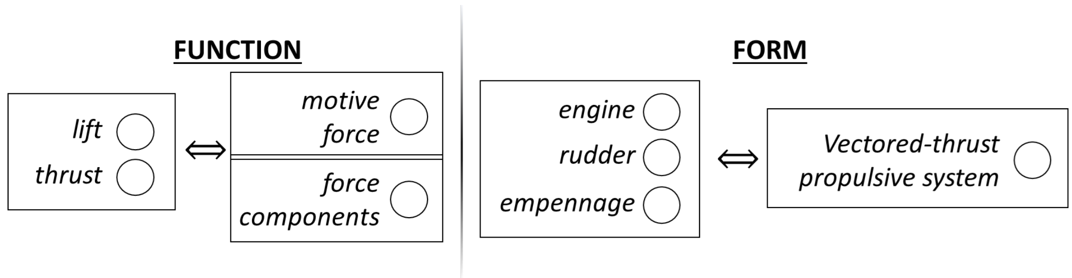

Fig. 5 A graphical illustration of different analogous ontologies, i.e. base categories used to coarse-grain an object of interest in order to describe it and predict its behaviour.

coarse-grain it into direction-based force components to match their purpose. And one could just as well define a total motive force as the base category, e.g. in anticipation of unconventionally driven (e.g. VTOL) vehicles. An abstract illustration of this feature is provided in Fig.5.

3. Life Cycle and Actors

The abstract nature of the coarse-graining formalism allows to extend the developments from the previous two sections to representation of functions and forms by object beyond physical phenomena alone. If extended to other life-cycle phases, which is the only truly relevant scope of analysis in the current optimisations of the industrial systems [16, 17], the features, be they functional or not in the given context, can be represented with any other objective variable representing a utility in the given context for whatever actor involved with the system. Revenue can serve as an intuitive example, where operating revenue can be the functional feature from the point of view of the operator, wheres the sales revenue can be that of the manufacturer. The same overarching logic of generalisation of the "function" to include local life-cycle-phase effects of contingent features can be applied across the life cycle and from the point of view of arbitrary involved stakeholders. Equivalently to wing forms that enable lift function at takeoff, the other life-cycle functions can be thought of having their own embodiments.

D. Function to Form Mapping

The possibility of many analogous ways to coarse-grain a system and what it represents in generalising the notions of functions and forms is at the core of the idea that this paper presents. Once the parameters are seen as coarse-grained objects that are all equal in the abstract realm they inhabit, the design exercise, i.e. the function-to-form mapping reduces to making correlations between the common set of abstract objects, grouped in two camps meaningful to the actors with respect to the utilities they expect at the life-cycle phase of interest. Function parameters and Form parameters.

The system design problem can thus be framed as simple search for optimisation of the life-cycle breakdown of the functions ("functional features") and the forms (which come along with the "contingent features" that locally oppose functional behaviours). As such, any design exercise ranging from the disciplinary developments of isolated systems, to multi-actor multi-system life-cycle based design processes - and across the design space - can be framed and carried out fundamentally the same way. For an elaboration of a system architecture preliminary design method applying these principles, the interested reader is referred to the associated work by the same authors. [17]

III. Civil Aeroplane Design Space

For the sake of ergonomics, the reviewed literature on the innovative is divided into two distinct categories, representative of two adjacent coarse-graining levels:

1) Whole-system, that is whole-aeroplane-level concepts.
2) Subsystem-level, that is concepts dedicated to sub-vehicle innovations, e.g. of propulsive systems, structural assemblies, of non-propulsive systems.

For a more in-depth discussions of certain parts of the innovative design space, the interested readers are referred to review papers by Brelje&Martins on the (hybrid-)electric propulsion aeroplanes [18], by Kim on distributed propulsion aeroplanes [19], by Bijewitz et al. on aeroplanes employing aero-propulsive synergies [20], as well as Gohardani [21] on distributed propulsion aircraft, and Abu Salem et al. on hybrid-electric aircraft technologies [22].

A. Innovative Whole-Aeroplane Architectures

This section presents the collected innovative aeroplane architectures; they are visualised in Fig.**??**. While possibly not grasping the entirety of the available concept space presented by the community, the choice is deemed sufficient to support the argument of the paper. For simplicity of the argument and demonstration, all the examples will be discussed from the in-flight perspective, unless otherwise noted.

Even the first visual glance at the concept pool will reveal difficulty to coherently characterise the vehicles by the airframe shape alone. While majority of the concepts does rely on the Tube&Wing composition of the forms, with clearly delineated fuselage, wings, and the engines, this categorisation breaks down in the parts where forms synergise, most commonly between the airframe and the propulsive system, which is the most represented form of function-to-form mapping.

Firstly, concepts like *VoltAir* [23], *Nautilus* [24], *I-6* [25], *Sugar FREEZE* [26], *DisPURSAL* [27] Project propulsive fuselage, *EcoPulse* [28], *D8* [29], *StarC-ABL*, *X-57 Maxwell* [30], *AMPERE* [31], *DRAGON* [32], *NOVA*[24] and *WrightElectric* [33] are observed. All those concepts retain the basic ancestral Tube&Wing morphology in different configurations thereof, and their common characteristic is synergising of the propulsive system with different parts of the airframe in search of some form of performance benefit. For instance, *VoltAir* [23] or *TailWind* [34] employ the boundary-layer ingestion concept in order to reduce its vehicle-level drag while providing the necessary propulsive force at the same cost. The same principle is employed with any of the presented concepts whose propulsive systems are embedded into the airframe. Depending on size and the mission profile, not all the concepts rely solely on single propulsor to carry out these functions. *Sugar FREEZE* concept employs the rear propulsor in order to reduce the fuselage drag, as well as the *DisPURSAL* concept.

Concepts like *EcoPulse* and *X-57 Maxwell* synergise airframe and propulsive system by employing the distributed propellers to enhance the lift capabilities of the wing, and enable lateral control capabilities at the benefit of reduced control surfaces - all of which can snowball into wing size (that is drag and weight) reduction. In case of *X-57* this is of utter importance as the aircraft is fully electric, and it needs all the weight allowance to carry the batteries. Furhermore, *X-57* stands out somewhat with respect to its counterparts. The distributed propellers are a form that is not necessarily dedicated to propulsion, but only to support the aerodynamic lift generation. Once the cruise conditions are reached, the propellers retract, in order to not create disturbing aerodynamic effect/drag.

Concepts like *AMPERE* and *DRAGON* represent a similar approach to the above two groups, combining the big number of distributed propellers to enhance their aerodynamic capabilities. These concepts also employing boundary-layer ingestion to reduce the drag penalty at the whole-vehicle level. The same is true of *Claire Liner* [20] and *D8*, with the same function-to-form mapping scenarios materialised with the fuselage instead of the wings. Concepts like *eThrust* [35] or *H-Series* [36] clearly lie somewhere in-between with their hybrid airframe shapes.

Forms like *Flying V* [37] or *Sugar RAY* [26] present another often-seen potentially optimal synergy, the so-called "Flying Wing" or "Blended-Wing-Body", which would be more apt label for the idiosyncratic form of the *Flying V*. Such scenario can be described as function-to-form mapping improvement in terms of the conventional paradigm as it conceptually tasks the same form to carry out the functions of lift, useful space provision, and some control and stability, depending on the details of the adjacent control surfaces. Ultimately, these can synergise further with the previously described propulsive system synergies, in order to yield even higher function-to-form mapping scenarios. Concepts like *N2-B*, *Ascent 1000* [38], *SAX-40*, *BW-11* [39], *N-G BWB* [40] *Zero-e* [41] and most of all *N3-X* [42] employ distributed boundary-layer-ingestion propulsion, enabling them conceptually to mutualise most of the in-flight functional features of the aircraft onto a single morphologically minimal form.

Furthermore, another common denominator for most of the presented concepts is reliance on hybrid-electric propulsive and power train. While this system architecture is mainly concealed within the airframe, and as such not exposed to the external drag influence (except unavoidably the propulsors), these systems are contributing significantly to search for higher performance optima by function-to-form mapping increase in two ways. Firstly, by uncoupling their local functions of energy conversion, transmission and use for propulsion [43] from a single system-level form that is the conventional gas-turbine engine. That way they enable the favourable pressure gradients created by the engine propulsors to be placed in the zones of airframe-adverse pressure gradient such that they improve the vehicle-level performance. Furthermore, innate properties of the electrical systems, whose dynamic response is superior to that of the gas turbines and they do not experience power lapse with altitude either - they can easily reconfigure power distribution in-operation in order to locally adapt delivered power and performance in unison with the gas turbine engines (if hybrid scenarios e.g. *ECO-150* [44] and *WrightElectric*) or with the airframe (either if hybrid like e.g. *e-FanX* [45] or full-electric *C-Liner* [46]).

Alongside all the possible variations, of which only a small sample was tackled in this discussion - most of

Fig. 6 Summary of innovative whole-aircraft concepts.

the presented concepts target drastically different operating profiles ranging between small commuters to very-long range airliners. This reinforces the case of the necessity of an abstract method to capture all the different theoretical possibilities.

A simple conceptual illustration of what function-to-form mapping represents and how it reflects the design space tendency with respect to selected aeroplane-level in-flight features (functional and contingent on them) is presented in Fig.7.

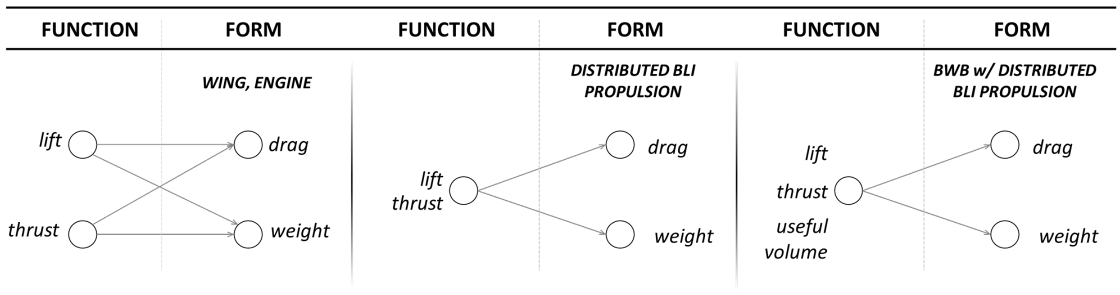

Fig. 7 Illustration of the function-to-form mapping tendency seen for the innovative vehicle concepts, illustrated using functional and contingent system features introduced in Chapter II.

B. Innovative Subsystem Architectures

Discussion on hybridisation and electrification that brings about various architectural distribution and operational scenarios on the road to better function-to-form mapping is an illustration of how ambiguous it might be to consider optimisation of an isolated system. (formerly engine) This reveals the conceptual lock-ins owing to what historically became a habit of internalising identification of a single function with a single form, as has been the case with the propulsive system, which in the contemporary era might tend towards new forms that transcend the confines of its traditional engine/power-plant form. Furthermore, the same argument can be applied to the mentioned boundary-layer ingestion concept, which in various ways synergises propulsive function with aeroplane level-drag at different airframe posts (fuselage, wing, or broader for flying-wing shapes).

Notwithstanding the book-keeping and semantic pedantry, it is instructive to take a brief look at the lower coarse-graining system levels, including subsystems and components, as arguably the same tendencies seen before can be observed. At this level, the reason is made on the basis of system-level features as dubbed in subsection II.C.2, notably phenomena such as compression, fluid transmission, heat exchange, etc, all of which build up to generate the whole-system level effects.

A somewhat more conservative propulsive system innovative concept from the gas-turbine engine design space is of interest to point out: intercooled core turbofan engine, and intercooled recuperated-core turbofan engine, illustrated in Fig.8. [47] These innovative propulsive architectures rely on the presented idea that forms can be employed to reduce contingent impacts features of the system as well. One such typical problem in gas-turbine engines and heat systems in general is heat. On the one hand there is excessive heat which needs to be controlled/evacuated, lest it reflects badly on other life-cycle aspects such as manufacturing, maintenance cost or reliability/safety. On the other hand all heat that is dissipated to the environment represents energy that is irrevocably lost. Notwithstanding thermodynamic limits that draw strict boundaries on how much of the heat energy can be recovered at most - efforts for reducing heat waste are always relevant to the designers. Intercooled engines design channels to pass from the core compressor through the bypass-duct heat exchangers prior to re-entering the compressor stage. That way, the gas temperature can be reduced before further compression is attained, thus contributing to overall thermodynamic performance at the same hypothetical maintenance cost penalty. In the coarse-grained abstract description of a system as a life-cycle, this would qualify as an increased function-to-form mapping, as it increases the performance of functional features (pressure ratio) for the same price paid in terms of features contingent on those. (maintenance cost) The same is true for the intercooled-recuperative cycle, which simply adds another functionality to recover the waste heat from the hot jet stream, and bring that energy back to the air prior to it entering the combustion chamber. This concept synergises the waste heat with the heat-exchange process of the gas-turbine core cycle, resulting in reduced need for injected fuel.

The focus on inter-cooled example was purposefully made, despite its obvious shortcomings. The added components to enable these new synergies would themselves add to the increased manufacturing and maintenance costs for instance,

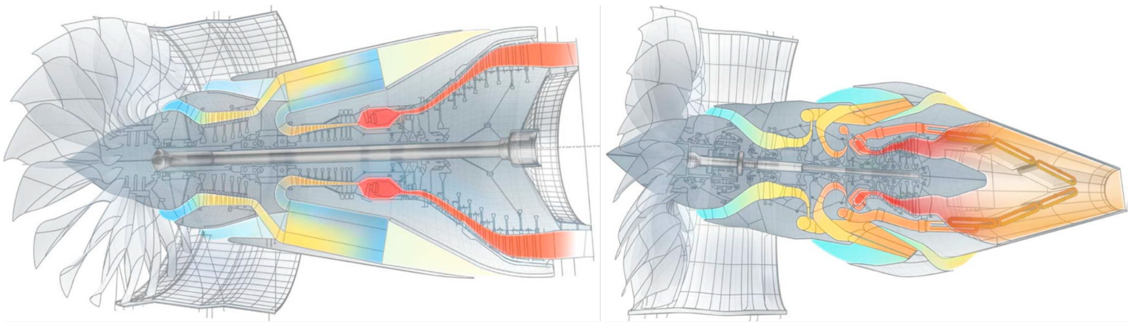

Fig. 8 Intercooled and recuperative core concepts for turbofan engines. (from [47])

as well as the overall weight of the system. But this does not change anything with respect to the overall thesis of the paper that the overall optimisation trajectories point in the direction of synergising systems properties across different levels of scale and/or life cycle. In that framework, any roadblocks to practical implementation will be a consequence of freezing the boundary around the engine and trying to change its features dramatically in isolation, where the optimisation objective is on the whole aeroplane level.

Even in isolation, systems could seek new function-to-form mapping peaks through component optimisation. Theoretical components like structural batteries, which would map energy storage and structural synergy onto a single form is a candidate. For the sake of argumentation, even more outlandish proposals power-generating aeroplane window glasses visible in the press can be mentioned. [48]

Although the enunciated focus of the study was civil aviation, a lot of useful insight can in principle be gained from the military concepts, which are always seeking extreme performance peaks at minimal weight and physical exposure.

IV. Discussion

The starting point for the analysis is the conventional Tube&Wing architecture which, for the purposes of this preliminary discussion is portrayed as having a roughly fully segregated functional division, mapping one function to one form: thrust produced by the engine, lift by the wings, cabin air conditioning performed by the dedicated environmental control system, vehicle stability by the tail surfaces, and so forth. Apart from being a convenient starting point for the analysis, this image is equally interesting for historical reasons, since the very first fixed-wing aeroplane concept proposed by Sir George Cayley in 1799 formulates a force breakdown necessary to enable fixed-wing flight [49]. The opposite side of the drawing proposes a form to enable those functions with what would now be referred to as one-to-one F-F mapping. (Fig.9)

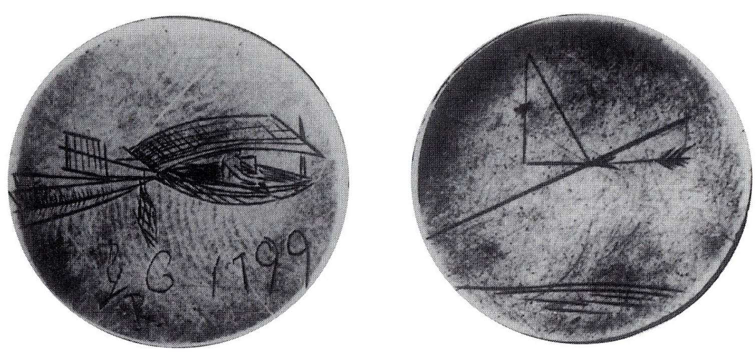

Fig. 9 The first documented definition of fixed-wing aeroplane concept on the eponymous Cayley's coin. The *two sides of the coin* can be seen as representing aeroplane functions and the associated forms.

Going further down the lanes of history, after the pioneering Wright brothers flight into the XX century, a notable example of such evolutionary trend is devising of load-carrying structural skin, which resulted in tremendous aeroplane drag improvement through removal of struts and wires which had been indispensable structural elements for the early aircraft. The same is true with subsequent inclusion of various subsystems and components, with performance gains enabled by introduction of NACA cowlings to reduce the reciprocating engine drag, or devising of the Meredith effect which evacuates engine heat while simultaneously acting on airframe drag reduction. Furthermore, retractable landing gear brought about removal of in-flight drag, putting it back to use during final approach and landing. Later on, the big airliners saw mergers of subsystems on the engine and environmental control system, where both get their initial air compression from the engine. Civil airliners also benefited greatly from equipping the wings with fuel tanks, and by increasing use of the fuel as heat-exchanger for various adjacent systems. Furthermore, since the mid-XX century this feature could be put to further use with active pumping and active in-flight center of mass control for improvement of the aircraft stability and trim drag.

When looked from a distance, or from the abstract point of view which puts all of the evoked developments on the same footing - it falls back on the common denominator that the form is proverbially *costly* to create, in the world of the artificial just as much as in the world of the naturally evolved systems. Materialising a function requires investment in terms of matter, energy, time, or financial cost. Most importantly, materialising a function will tend to incur a penalising effect on one system utility or another, exactly for the reason of unavoidable contingent features such as drag, weight, heat loss, and so much more.

However, arguably all of the above previously reviewed and analysed concepts experience penalties that do not necessarily stem from the instantaneous view of physical-performance figure of merit, but the fact that there is often little visibility in a broader trade space where superior global optima could be sought. The implication of this statement is that aeroplane should be looked at not as an object that performs certain physical function under direct operation, but whose performance is described by comprehensive figures of merit capturing various performance aspects from the entire life cycle and from the point of view of all the involved stakeholders.

The explored gas-turbine engine and hybrid-electric propulsive system successor is a poignant example of how historically all the relevant lower-level system functions could be contained in a single form (at face value being exactly what this paper argues for). However, as long as it is the higher-level performance optimum that is sought, the local-level mappings are not relevant. An argument follows that the full vehicle-level function-to-form mapping, could be made on the basis of more finely-grained description. This would arguably help capture new performance peaks and over a complete life cycle.

The tendency following from the comparative analysis of the different architectures surveyed in the previous chapters indicates a trend that can arguably be use to describe a major part of the aeroplane evolution from its earliest days to the contemporary era. Fig.10 attempts to illustrate that idea with the pioneer era aeroplane on the one side of the extreme: sparse F-F mapping, low performance, and hypothetical future flying-wing aeroplanes on the other, with dense F-F mapping and superior performance levels. Historically, starting from a somewhat decomposed form of wings being dedicated to providing lift, propeller for thrust, engine for power production, tail surfaces and/or canards for stability, and even intricate net of struts and wires for dedicated structural integrity (see Fig10 from [50]) - the concept has been evolving towards higher efficiency and higher performance alike by mapping more functions to less forms at various scales of the system.

V. Conclusion

This paper formulates a new, abstract, system-based manner to discuss fixed-wing civil aeroplane design space. It leans on a review of innovative fixed-wing civil-aeroplane system architectures. The review is extended with additions of certain historical developments of interest, which reinforce the underlying reasoning behind the paper that all aeroplanes forms, thus including the historical ones, are different members of the same set of object.

The need for the presented elaboration is motivated by the observed discrepancy between limited, category-based taxonomy commonly used by the community to categorise aeroplanes, and a theoretically continuous design space inferred from the numerous innovative architectures found accumulated in the literature in the past decades. A generic recursive coarse-grained parametric formalism is presented as abstract backdrop for system representation. System engineering principles are employed to formulate the concepts of form and function. Extending these principles, system design is formulated as exercise in function-to-form mapping that enables to search for optima across complex spaces with multitude of actors involved in the system design.

The reviewed system architectures are presented from the standpoint of the function-to-form mapping framework, and an inference is drawn on a historical tendency to map increasingly higher number of aeroplane functions onto same (or smaller) number of forms in search for higher performance and efficiency.

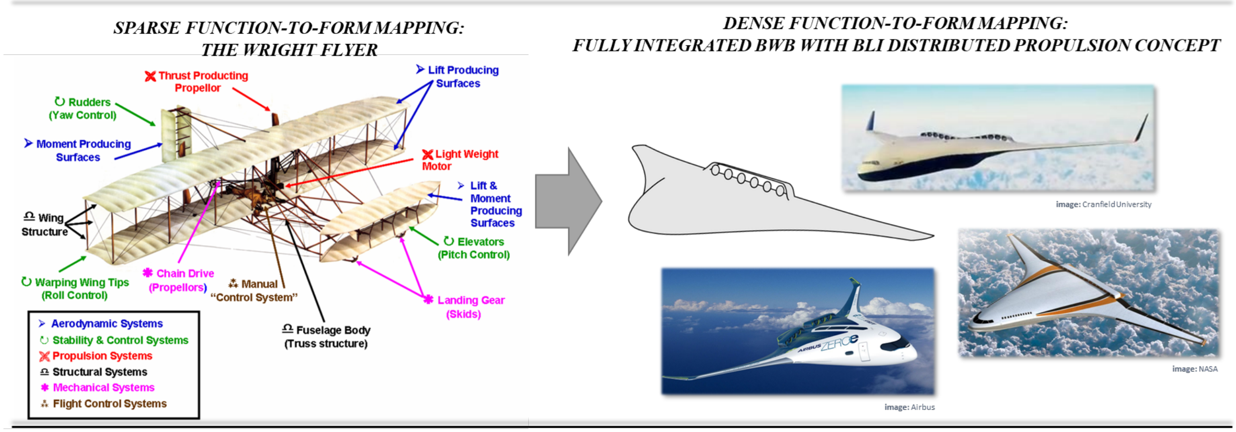

Fig. 10 Wright brothers' "Flyer" as a rough depiction of the historical initial assembly of scattered forms, each dedicated to a unique function (illustration from [50], and the other side of the potential evolutionary pathway: concept mapping almost all the major aeroplane-level functions onto a single form (based on [13]).

Ongoing activities around the presented framework include:

- Extending the review to encompass other parts of operation and life cycle of the concepts found in the literature.
- Correlating the F-F mapping with relevant performance and efficiency indicators for a rigorous evaluation of the identified tendency, to be further used in top-down aeroplane system architecture design methods developed by the same authors [17].

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