A Paleoaerodynamic Exploration of the Evolution of Natures Flyers and Man's Aircraft and Options for Future Technology Innovations.



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ABSTRACT

This presentation will provide insights and observations of fascinating aspects of birds, bugs and flying seeds, of inspired aerodynamic concepts, and visions of past, present and future aircraft developments. Contrasting driving forces for the evolution of nature's flyers, and the corresponding evolution of commercial aircraft will be presented. We will explore similarities between nature's creations and man's inventions. In spite of the tremendous technological growth leading to today's' aircraft, there remains many critical areas requiring future significant technology based solutions. With the advent of UAVs and MAVs, the gap between "possible" and "actual" is once again very large. Biologically based technology development options will be discussed. Allometric scaling procedures will be used to explore size implications on limitations and performance capabilities of nature's flyers and nature in general. Biologically related technology development concepts including: bionics, biomimicry, neo-bionic, pseudo-mimicry, cybernetic and non-bionic approaches will be discussed and illustrated with examples. Various technology development should include a synergistic coupling of "discovery driven", "product led" and "technology acceleration" strategies. The overall objective of this presentation is to inspire the creative nature existing within all of us..

Keywords: Nature's flyers, evolution, aircraft technology, bionic, biomimicry, neo-bionic, pseudo-mimicry, cybernetics, allometric scaling, innovation strategies

1. INTRODUCTION

Our words and writings are the messengers of our thoughts. Yet at times they must be accompanied by an interpreter. I therefore think that it is important to clearly define my interpretation of the title of this presentation, in particular the word "Paleoaerodynamic". The common formal definition of the prefix "Paleo" is generally similar to the Webster definition "A prefix meaning old or ancient". I certainly did not intend to discuss "old or ancient aerodynamics". My use of the prefix "Paleo" is more closely related to a definition of Paleontology by the University of California Museum of Paleontology. We will define "Paleoaerodynamics as a rich field, imbued with a long and interesting past and an even more intriguing and hopeful future".

In this presentation we will attempt to get a glimpse of insights and observations of some fascinating aspects of birds, insects and flying seeds, of inspired aerodynamic concepts, as well as visions of past, present and future aircraft developments and further opportunities for aircraft innovations. Through this brief journey for understanding, we will explore the fascinations of nature, the struggle to fly and the ultimate successes of our flying machines. At times our path may seem to wander from seeming unrelated thought to unrelated thought. However in each bend in the road it is hoped we will gain a greater insight and greater appreciations of nature, and of our industry.

Man most certainly has always been fascinated, and inspired by the dream of flying by observing birds soaring in the sky and flittering from tree to tree. The British aviation pioneer Sir Hiram Maxim once wrote: "Man is essentially a land animal and it is quite possible if Nature had not placed before him numerous examples of birds and insects that are able to fly, he would never have thought of attempting it himself". Many of mans flying or gliding inventions have indeed been inspired by natures creations.

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Dr. John McMasters¹ said "The study of the biomechanics nature had (and still has) much to teach us regarding the possible future development of our art and our technology. Modern birds in particular already fully and elegantly embody a number of items that have been the subject of much research and development in aviation in recent decades".

We will briefly look and discuss various perspectives of the evolution Nature's flyers and the evolution of man's aircraft. An interesting view of the contrasting evolution-of-flight driving forces between nature and commercial aircraft will be introduced. We will explore many of nature's fascinating flying things including birds, insects and seeds and will also shows similarities between Nature's creations and Man's inventions. In spite of the tremendous technological growth leading to today's' aircraft, there remains many critical areas requiring future significant technology based solutions. With the advent of UAVs and MAVs, the gap between "possible" and "actual" is once again very large. Various technology development strategies will be discussed along with the pros and cons for each. It will be shown that future technology developments should include a synergistic coupling of "discovery driven", "product led" and "technology acceleration" strategies.

Biologically based technology development options will be discussed. Allometric scaling procedures will be used to explore size implications on limitations and performance capabilities of nature's flyers and nature in general. We will look at nature related sources and opportunities for future innovative developments where biomics, bio-mimicry, neobionic, non-bionic, Pseudo-Mimicry and cybernetics concepts of innovation are introduced and discussed. The importance of learning to see and not just look, and learning to hear and not just hear, and learning to wonder why and then conceive how it might apply, will be offered as key success elements for advancing our state of the art and science.

2. EVOLUTION OF EVOLUTION

Some of the key events in the evolution of the theory of evolution are shown in figure 1. The grandfather of Charles Darwin, Erasmus Darwin had published in his book "Zoonomia" in 1795 early thoughts on the origin of life. Erasmus Darwin wrote that warm-blooded creatures developed from "one living filament" and acquired new parts "in response to stimuli" and that all improvements were inherited by successive generations.

Jean-Baptiste Lamark in 1809, published his beliefs on the origin of life in "Philosophie Zoologique". Lamark incorporated two ideas into his theory of evolution that in his day were generally considered true. Lamark believed that individuals develop characteristics that are useful in response to specific needs and these characteristics were retained by usage. He also believed that individuals lose characteristics they do not require (or use). Subsequent generations were thought to inherit all acquired traits. These unique beliefs of Lamark were ultimately disproved.

Charles Darwin published the "Origin of Species" in 1859 in which he defined that the process of "natural selection", (which is commonly called the survival of the fittest), occurring over millions of years has resulted in all the species of life. This is generally considered to be one of the greatest scientific discoveries of all time². It was once stated "that never has so much knowledge been based on so little facts".

Gregor Mendel defined the statistical laws of inheritance and is considered the father of modern genetics. The notion of a gene has evolved with the science of genetics, which began when Gregor Mendel noticed that biological variations are inherited from parent organisms as specific, discrete traits. The biological entity responsible for defining traits was termed a gene. Prior to Mendel's work, the dominant theory of heredity was one of blending inheritance, which proposes that the traits of the parents blend or mix in a smooth, continuous gradient in the offspring.

Thomas Morgan (1912c) identified that genes carried on chromosomes defined the mechanical basis of heredity. He is generally considered to be the father of the modern science of genetics. The biological basis for inheritance remained unknown until DNA was identified as the genetic material in the 1940s. DNA not only confirmed the reality of evolution, it also showed at the most basic level how it reshapes living things. All organisms have many genes corresponding to many different biological traits. In cells, a gene is a portion of DNA that contains both "coding" sequences that determine what the gene does, and "non-coding" sequences that determine when the gene is active (expressed). James Watson and Francis Crick in 1953, defined the double helix structure of DNA. This discovery unlocked the mystery of how genetic information is passed from one generation to the next³.

Research studies by Peter and Rosemary Grant, (1970c) demonstrated that natural selection can cause evolutionary change in real time rather than only over thousands of years as Darwin had believed. More recent studies have shown evolution works not just by changing genes, but by modifying the way those genes are turned on and off by a "genetic switch". It therefore appears that the primary source for evolution turns out not to be gene changes but changes in the

regulation of genes that control development. For example, a giraffe does not have special genes to make a long neck. Its neck growing genes are the same as those for a mouse; they are just switched on for a longer time.



Mice and humans (indeed, most or all mammals including dogs, cats, rabbits, monkeys, and apes) have approximately 29000 genes. In addition many of the same genes control similar functions on the different species.

The current understanding of the evolution life indicates that four conditions must be met in order for a species to exist⁴:

- It must work mechanically and chemically
- It must be capable of being coded
- It must be able to survive at all stages of growth
- Its Design Must be Able to be Evolved Through a Series of Forms From Some Other Existing Form, Each Form Being Viable in its own niche of the nichewise Progression

The process of evolution can be described as a gradual unrelenting improvement of living systems in response to local environmental conditions. The process of evolution in contrast to man's technology developments, does not "design" by working to specific goals or objectives, instead, evolution blindly cobbles together myriad random experiments over thousand of generations resulting in wonderfully elegant organisms whose goal is to stay alive long enough to produce the next generation which then launch the next round of random experiments².

The nature of the evolutionary processes of biological systems is fundamentally limiting since every new feature must develop from an existing feature. Consequently, there is no chance of making the sudden great revolutionary technology developments that are so common in the history of technology⁶.

3. COEVOLUTION

Coevolution is one of the most powerful driving forces in evolution. Coevolution involves the joint evolution of two or more species as a consequence of their ecological interaction. Each species in a coevolutionary relationship exerts strong selective pressures on the other, thereby affecting each others evolution. The close, prolonged association between two or more different organisms of different species that may, but does not necessarily, benefit each member is called symbiosis. The major types of co-evolutionary relationships include:

- 1. Mutualism which is a cooperative coevolutionary symbolic relationship in which both species benefit.
- 2. Predation which is a competitive coevolutionary relationship between a predator and its prey.
- 3. Amensalism which is a symbiotic coevolutionary relationship between organisms in which one species is harmed or inhibited and the other species is unaffected.
- 4. Commensalism which is a symbiotic coevolutionary relationship between two species in which one derives some benefit while the other is unaffected.

Examples of two types of mutualism relationships are shown in the figure 2. Bumblebees as well as hummingbirds both obtain nourishment from flowers and various trees and in the process they spread pollen to other trees and pollen. This is an example of a service-resource relationship. An example of service – service symbiosis is the relationship between clownfish that dwell among the stinging tentacles of sea anemones without being harmed. This protects the clownfish from larger predators and at the same time the clownfish protect the anemones from the butterfly fish which other wise

would destroy them.

Service - Resource Relationships

Service - Service relationships



Fig. 2. Examples of Mutualism Coevolutionary Relationships

Aposematism which is most commonly known in the context of warning coloration describes anti-predator adaptations where a warning signal of potential danger or discomfort associated with a potential prey item to potential predators. It is one form of natures "advertising" signals, with many others existing such as the bright colors of flowers which lure pollinators. The warning signal may take the form of conspicuous colors, sounds, odors or other perceivable characteristics. Aposematic signals are beneficial for both the predator and prey, who both avoid potential harm. As shown in figure 3, aposematic evolutionary developments can occur in many species of mammals, insects, reptiles and fish.



Fig. 3. Examples of Mutualism Aposematic Type of Signals

The bright colors of the yellow-winged darter dragonfly warns birds and other predators of its noxious taste. The contrasting black and white colors the skunk warns other animals and humans of its noxious smell. The bright colors of the cuttlefish and coral snake warn of their toxicity. Figure 4 shows additional examples of aposematic mutualistic developments in nature. The yellow jacket and the bumble both have highly visible yellow and black colorings to warn predators of their painful stings. The color patterns that each has evolved are very similar. This is an example of Mullerian mimicry and benefits both species by reducing the educational "cost" for each species to "teach" potential predators of their painful stings. The harmless hoverfly has evolved a very similar color to exploit the aposematic protection proved by the color patterns of the yellow jacket and the bumblebee



Fig.4. Mimicry in Nature →Mutualism

Examples of predator and prey camouflage patterns that have evolved are shown in figure 5.



Fig. 5. Camouflage → Coevolutionary Predation Examples

Coevolutionary develops of bats and moths are shown in figure 6. Bats love moths and have developed echolocation as a means to locate and capture moths. Moths in turn have subsequently developed soft coverings to absorb the bat chirps and eliminate to some degree the benefits of echolocation. The bats then developed new chirp frequencies to be able to locate moths even with the soft coverings. The moths responded by developing enhanced stealth characteristics together with jamming techniques with their own chirps and new evasive maneuvers. Bats subsequently developed new elaborate flight paths and the ability to turn their chirps on and off, to confuse the moths. The arms race continues.



Fig.6. Coevolutionary Developments of Bats and Moths

4. EVOLUTION OF NATURES FLYERS

The evolution of flight in animals and in man's flying vehicles as shown in figure 7 has steadily progressed over a period of time of approximately 330 millions of years starting with the first winged insects⁷. Pterosaurs followed nearly 140 millions of years later. The earliest bird like animals first appeared 150 millions ago followed by early flowering plants many of which have exploited flight like mechanisms to disperse their seeds. Modern insect orders, modern bird orders and bats made their appearance about 55 to 75 millions of years ago. This corresponds to the Cretaceous /Tertiary Mass Extinction Event which occurred approximately 65 millions of years ago. Successful powered flight by man has existed over a minuscule period of slightly more than 100 years.



Fig. 7. Evolution of Flight

Flight is one of the most demanding adaptations found in nature because of the physical challenges of moving in air under the persistent influence of gravity. Therefore flyers in nature have been subjected to strong selection for optimum morphololgy. Nature's flyers as well as man's air vehicles can be described fundamentally as systems of systems. Major subsystems such as aerodynamic, structures, flight controls, "propulsion", "mechanical", "navigational", "fuel" systems, "air conditioning", and "safety / security" systems inherent in man's flight vehicles have parallels within Nature's flyers.

There exist strong synergisms between all of the functionally interdependent component subsystems. Prior developments in one subsystem are often both enabling and necessary for subsequent advancements in other subsystems. Consequently "technology" advancements in Natures flyers and in aircraft include by necessity include multiple sequenced and serendipitous developments. The "survival of the fittest" selection process for nature implies that each subsystem is in itself an optimum solution within the confines of the overall optimized system. Nature has, however, evolved four convergent solutions for the challenge of flight. These include birds, bats, pterosaurs and insects whose wing structures are shown in figure 8.

Bats, birds, and pterodactyl wings not only perform the same function of providing the means of flight, but they are also examples of homologous structures since the limbs of all these organisms contain many of the same sets of bones. These have been passed downed to all these different animals from a common ancestor. These wings are also homologous to the human arm and hand. The wings of insects are analogous structures relative to the other previously discussed wings because of the fundamental differences in their internal anatomy even though they perform the similar function of flight.



Fig. 8. Natures Wing Designs

The design of an insect wing at first glance would appear to be very complex. The basic design is however rather simple and extremely elegant. The wings of the dragon fly are strengthened by a number of longitudinal veins which have cross connections that form closed cells in the membrane. The patterns that result from the fusions and cross connection of the wing veins are often diagnostic for different evolutionary lineages and can be used for identification of the family level in many orders of Insects. The general design of the wing can be understood by applying the simple intersecting membrane sketches shown in figure 9.

In these sketches, two large parallel membranes with tension "T", are joined by a criss-cross membrane with tension "t". In Sketch "A" the tension "T" in the large veins is much larger than tension "t" in the cross membrane. The cross membrane therefore intersects the large membrane at a 90° angle.

In Sketch "B" the tension "T" in the large veins is only slightly larger than tension "t" in the cross membrane. The cross membrane therefore pulls the large membranes in slightly such that the intersection angel is approximately 100° to 110° .

In Sketch "C" the tension "T" in the large veins is equal to the tension "t" in the cross membrane. The cross membrane therefore pulls in the large membranes so that the intersection angel is approximately 120° .

We can now define the basic design of the by four simple rules:

- 1. Main Veins tend to run parallel out the wing
- 2. When two large veins are so near that only 1 Cell is between, the Cells are quadrangles with, the thin partitions meet sides at right angles
- 3. With 2 cells between ribs, Cells fit each other with 120° angles and meet the ribs at right angles (pentagons)
- 4. With many cells between ribs, all angles in common tend to be 120° (hexagons)

As shown in the figure, these four rules do indeed define the general characteristics of the dragon fly wing structure.



Fig. 9. Elegant Design of an Insect Wing

Other natural fliers include the seeds of wind pollinating plants that evolved to provide their parent species one of the most remarkable and effective of all seed dispersal methods, riding the wind and air currents of the world⁸. Some common examples are the milkweed seed, which may be considered a direct natural antecedent of the parachute, and the maple seed, a natural prototype of the autogiro. Of considerable historical interest, because it demonstrated to aviation pioneers the feasibility of constructing a true self- stable tailless airplane, is the gliding seed of the Java palm tree, zanonia macrocarpa. These will be discussed later in this report.

Although winged insects were the first creatures to fly, our subsequent discussions will primarily focus on the developments of the flying capabilities of birds.

Flight capability opened up new sources of food, made escape from earthbound predators easier and increased the safety of living and breeding quarters. Impenetrable barriers such as mountains, oceans or rivers became easily navigable. Ultimately flight made it possible to follow favorable climates and changing food sources by means of seasonal migrations. Probable steps in the evolution of flight in birds are shown in figure 10.

The initial steps in the evolution of flight were fundamentally driven by the needs of *survival*. These needs included safety from predators for both the individual and their offspring and more effective means of foraging. The early flight capabilities included parachuting and rudimentary gliding abilities. The enabling anatomical changes included developing the fundamental structure of the wing including the incredible concept of the feather.

The next series of steps in the march of evolution provided more *efficient* gliding flight with some maneuverability and the initiation of slight flapping flight. These provided the ability to determine the direction of the glide and stabilizing movements for turning and landing. The anatomical changes included development of neuromuscular control for coordination wing of wing movements and more effective wing geometry shapes.

Subsequently evolutionary developments provided increased flight *functionality* and better flapping flight performance with some degree of maneuverability. The associated anatomical developments included better neuromuscular control and more sophisticated wing aerodynamic characteristics. Following evolutionary steps have provided the ability to fly *"higher, faster and farther"* by providing flapping flight with high maneuverability soaring and hovering capabilities.

Locomotion	Goal	Adaptations	Nature's "Technology" Drivers
1. Climbing [running]	Foraging and avoiding predators	Climbing agility [running agility]	
2. Parachuting (steep gliding); [hang-gliding]	More effective foraging and avoiding predators	Larger forearm surface (propatagium, feathers)	Survival
3. Gliding	Optimal foraging, movements between foraging areas	Larger wings, lower wing loading	
4. Gliding with some maneuverability	Ability to determine direction of the glide	Neuromuscular control, wing coordination, wing camber	Efficiency
5. Slight flapping flight	Movements for stability, maneuvers in turning and landing	Higher aspect ratio, lower wing loading	Ententy
6. Flapping flight with some maneuverability	Better flight performance, commuting	Better neuromuscular control, more sophisticated wing features, camber for slow flight	Functionality
7. Flapping flight with high maneuverability , Soaring	Aerial prey-capturing, hovering etc. Soaring /Migration	Highly sophisticated wing features, slots, keeled sternum, musculoskeletal system like that of modern birds	Higher, Faster Farther

Fig. 10. Probable Steps in the Evolution of Avian Flight Capability

The varied developments of the eyes of predator birds and the eyes of birds that are the targeted prey as shown in figure 11 are an example of avian co-evolutionary developments. Most birds cannot move their eyes, Birds with eyes on the sides of their heads have a wide visual field, useful for detecting predators, while those with eyes on the front of their heads, such as owls, have binocular vision and can accurately estimate distances when hunting.



Fig. 11. Co-Evolutionary Development of Vision and Eye Structure 🗲 Predator vs. Prey

Many avian species focus on distant objects preferentially with their lateral and monocular field of vision. Consequently, birds will position themselves sideways to maximize visual resolution. For a pigeon, resolution is twice as good with sideways monocular vision as with forward binocular vision, whereas for humans the converse is true. When a prey type bird turns their head away from an object they are doing so to obtain a more accurate view.

Nature's flyers as well as man's air vehicles can be described fundamentally as systems of systems. Major subsystems such as aerodynamic, structures, flight controls, "propulsion", "mechanical", "navigational", "fuel" systems, "air conditioning", and "safety / security" systems inherent in man's flight vehicles have parallels within Nature's flyers. There exists strong synergism between all of the functionally interdependent component subsystems. Prior developments in one subsystem are often both enabling and necessary for subsequent advancements in other subsystems. Consequently "technology" advancements in Natures flyers and in aircraft include by necessity include multiple sequenced and serendipitous developments.

The unending process of evolution driven by the "survival of the fittest" is molded by local environmental effects and the demands of co-evolution including both responsive developments and those that provide competitive advantages. Consequently nature has produced many unique acceptable flying designs as evident in the approximately 8000 bird species, 1000 species of bats and 350,000 species of flying insects.

Figure 12 shows how the local environmental effects have shaped the bills of many species of birds as a result of different feeding adaptations.



Fig. 12. Effect of Different Feeding Adaptations on the shape of Bird Bills.

Birds are dramatically different from all other living creatures. Feathers, toothless beaks, hollow bones, perching feet, wishbones, deep breast bones and stump like tailbones are only part of the combination of skeletal features that no other living animal has in common with them. Figure 13 shows various systems of systems developments in the evolution of birds. The developments or adaptations that are shown in the figure are grouped according to:

- Weight-reducing adaptations
- Power-increasing adaptations
- Aerodynamic adaptations

Weight-Reducing Adaptations	Power-Increasing Adaptations	Aerodynamic Adaptations
Thin, hollow bones	Warm-blooded	Development of forelimb as a wing
Light feathers	Heat-conserving plumage	Infinitely variable morphing wing
Elimination of teeth and heavy jaws	Energy rich diet	Flow control adaptations
Development of the beak	Crop for storing food	Streamline bodies and Effective Wing Airfoil
Tail for steering	Gizzard for grinding food	snapes
Development of the forelimb as a wing	Devid sinculation	Function Driven Wing Characteristics
Development of the foreintib as a wing	Rapid circulation	Control device (eq. Tail. Tip Feathers, Dynamic
Extensive bone fusion	Large 4 chamber heart	Planform)
Branching air sacs	High blood sugar levels	Stability augmentation for naturally unstable
Syriny instead of trachea		system
Synnx instead of addred	Breathing synchronized with wing beats	3/30/11
	High rate of metabolism	

Fig. 13. System of System Adaptations in the Evolution of Birds

The pictures in figure 14 which were taken from the outstanding video by Gareth Jones⁹, show a kestrel hovering on up flow air currents on the windward side of a steep hill. Even though the air currents are moderately gusty, the kestrel is able to keep its eyes and head position remarkably fixed in space allowing continual and total focus on its potential prey¹⁰.



Fig. 14. Hovering Kestrel Demonstrating Structural and Neuromuscular Control

This is an excellent example of the impact of a bird's evolutionary structural and neuromuscular control adaptations and the resulting wing and tail movements some of which include:

- Pitch Stability and Control
 - A long, sturdy, movable dosoventrally flattened tail (e.g. Archaeopteryx)
 - Downward and upward movements of the tail
 - Fore and aft movements of the wing relative to the center of gravity
- Roll Stability and Control
 - Long, broad wings with rounded tips
 - Sweepback
 - Wing asymmetric dihedral like movements
 - Twisting the wings in different directions
- Yaw Stability and Control
 - Long, broad wings with rounded tips
 - Tail rotary movements
 - twisting And flexing the wings to change drag

In the vernacular of an aerodynamicist, the Kestrel hovering flight demonstrates a highly sophisticated flight critical dynamic morphing coupled aeroservoelastic control system.

The kestrel also provides a powerful message for success: "Keep Your Eye upon Your Goal"

5. EVOLUTION OF TECHNICAL FLIGHT

It is well documented ^{10, 11, 12, 13, 14} that the more successful of the earlier pioneers of manned flight were inspired by natures flying creatures and objects and were well versed in the then current understanding of flight mechanics. "Of all animal movements, flight is indisputably the finest. It may be regarded as the poetry of motion. The fact that a creature as heavy, bulk for bulk, as many solid substances, can by the unaided movements of its wings urge itself through the air with a speed little short of a cannon-ball, fills the mind with wonder".

The concept that the inspiration of natures flyers lead to experimentation, then the realization of manned flight and ultimately leading to the proliferation of flight capabilities through many airplane concepts is often the traditional view of the history of flight. However a more expanded view of the history of flight is shown in figure 15. Nature's evolutionary processes and man's technology development are all bound together by the underlying requirements that each must obey the same fundamental laws of physics, chemistry - and economics. However the evolutionary processes of biological flight are significantly different than the evolutionary processes of technical flight.



Fig. 15. View of the Evolution of Flight

A more expanded view of the evolution of flight is shown in figure 16 to highlight the fact that Man's desires, thoughts, and efforts to fly have occurred not just over the past "Century of Flight", but over a period of hundreds of years. As it will be shown, this evolutionary period was highlighted by the enhancement our Knowledge of Flight Dynamics (KFD), our Understanding of Flight Dynamics, (UFD) plus the sequential developments of critical and necessary supporting technologies.



Fig. 16. Expanded View of the Evolution of Flight

The initial tools that were available to the early pioneers of flight are shown in figure 17. These include the information, ideas and interpretations that they gleaned from observations of birds soaring, bats flying and Hummingbirds hover. We call this Visual Flight Dynamics, VFD. Otto Lilienthal (circa 1890) who is considered by many to be the pioneering father of flight stated "*In order to discover the principles which facilitate flight, and to eventually enable man to fly, we must take the bird for our model.*" This visual information formed the basis of their Knowledge of Flight Dynamics (KFD) from which they formalized their Understanding of Flight Dynamics, (UFD). It should be noted that knowledge and understanding are not the same, nor is all knowledge absolute, accurate or factual.



Figure 17: Early Aerodynamic Tools

6. EARLY UNDERSTANDINGS OF AVIAN FLIGHT

It is interesting to examine the details of the state of knowledge of the physics of bird flight as recorded in books that were published in the time period of the Wright Brothers initial flights^{11, 12, 13, 14}. Man's concepts of the nature and the physics of avian flight gradually developed from endless hours of marveling at the flight of birds over centuries of time. We have identified this source of information as VFD (visual flight dynamics). Early observations such as shown in figures 18 and 19 formed the basis of the evolving knowledge, KFD and understanding, UFD (not necessarily correct) that ultimately lead to man's initial attempts to fly.

One of the earliest recorded pictures of the observed nature of flight is shown in figure 18. This is a cave painting from about 11,000 years ago, of what appears to be a bird landing. The picture suggests that the artist had a rather accurate understanding of the use of wings during landing, including what appears to be the extended $alula^{10}$.



Fig. 18. Earliest Known Cave Painting of a Bird.

DaVinci's well known sketches of bird flight from about 1500 are shown in figure 19. These sketches also show his interpretation of the characteristics of the flow around the bird. The third daVinci picture shows the tail being deflected as a stabilizing mechanism. It is generally believed that these sketches were based more on his understanding of the physics of flight that on any particular flight observation.

The sketches by Borelli shown in figure 19, illustrate his concept of the manner by which birds fly as he stated in his masterpiece "De Motu Animalium" that appeared after his death in about 1680. "*Birds fly by beating the air with their wings. They jump as it were through the air just as a person can jump on the ground ----- Wing beats compress the air and the air bounces back.*" Borelli's understanding that the tail moved up and down to provide pitch control differed from the previously accepted belief advocated by Aristotle, that the tail acted as a rudder. Borelli also stated that birds change their horizontal direction by beating the left and right wings at different speeds similar the way that a "rower alters course by pulling harder on one oar than the other".



Fig. 19. Early Interpretations of the Nature and Mechanisms of Avian Flight

A very significant supporting technology development that provided valuable insight into the nature of flight was the chronophotographic gun that Etienne-Jules Marey¹⁵ perfected in 1882. With this instrument Marey was capable of taking 12 consecutive frames a second, and the most interesting fact is that all the frames were recorded on the same picture as shown in figure 20. With this instrument, it was then possible to observe the intricate motions of a bird or insect in flight. Marley's photographs were an early form of Visual Flight Dynamics, VFD.



Fig. 20. Marey's"photographic gun" capable of taking twelve exposures in one second. (1882)

Marley also made movies at high speed (60 frames per second). He is widely considered to be a pioneer of photography and an influential pioneer of the history of cinema. During the 1860s Marey focused on the study of flight, first of insects and then birds. His aim was to understand how a wing interacted with the air to cause the animal to move. He also devised some ingenious apparatuses such as a corset which allowed a bird to fly around a circular track while recording the movements of its thorax and wings.

Otto Lilienthal published the results obtained by him, working in conjunction with his brother, after long years of quiet scientific study and experiment, in 1889¹². This book contained the "discovery" of the driving forward of arched surfaces against the wind. Lilienthal said "The problems why a flying bird does not drop to the ground, how it is sustained in the air by an invisible force, may be considered fully solved so far as the nature of this supporting force is concerned." Figure 21 contain sketches of the shapes of various bird wing geometries, plus a sketch of the details of a stork's wing. It is obvious that the Lilienthal brothers had a obtained a rather thorough understanding of the flight features of a bird. They then spent a period of approximately 5 years over which they conducted approximately 2000 glider flights.

Sketches of Various Wing Geometries



Fig. 21: The Lilienthal's Bird Flight Concepts

Five methods of bird flight were distinguished¹¹ in the period in which the Wright Brothers entered the scene. The first method was called *"rowing flight"* (corresponding to the modern day vernacular of flapping flight), *"was formulated by a combination of chronograph measurements together with a series of photographs. The photographs were obtained simultaneously from three directions showing the showing the movements of the wings at various sequential moments."* (The early concept of early flight related the mechanics of flapping flight to the motion of rowing a boat. This is substantially different that the actual mechanics of flight.)

The second method called Gliding flight was defined as "rowing flight interrupted by the passive flights - the gliding. During gliding the flapping of the wings is halted, and the flight is sustained by the kinetic energy generated during the rowing flight". (This definition corresponds to our present day concept of bounding or intermittent flight).

The third method was called soaring. "During soaring, the bird remains over a point on the ground without flapping its wings; soaring is rendered possible by upward currents of air, forming over wooded land and on rugged rocks. The activity of the muscles is confined, in this case, to feeble balancing turns of the stretched wings about the body longitudinal axis."

The fourth method was called sailing. "Sailing is seen frequently with sea gulls following ships or progressive waves This movement is caused by the wind, reflected upwards after striking the sails or crests of the waves, holding the bird at a constant height and at a constant distance away from the sail or the wave crest, as the case may be. The difference between sailing and soaring is, that the animal not only remains at a constant height, but in the former case also is driven forwards."

The fifth method was called circling. The "*explanation of the circling of birds is attended with especially great difficulties*". Apparently the physics of thermals caused by local uneven heating of landmasses was unknown at that time. These thermals result from a central ring of revolving air with a core of rising colder air. The birds circle to remain in the core of rising air and then glide between other thermals.

It is interesting that there was no specific mention of hovering, either as a form of active flight in the case of humming birds rapidly beating their wings, or as a form of passive flight as in the case of the Kestrel riding rising upward currents over a steep hill as the previously shown in figure 14.

7. MAN'S EARLY FLIGHT CONCEPTS

The earliest concepts and attempts at flying were all based on attempts to directly emulate the flight of birds as shown in figure 22. Leonardo said that "a bird is an instrument working according to a mathematical law. It lies within the power of man to make this instrument with all its motions." Leonardo like many of the early pioneers of flight that followed, based on their observations of birds, believed that in order to fly, man would need a pair of flapping wings. These

devices became known as ornithopters. DaVinci's concept of an ornithopter was developed in the 1486 to 1490 time period, However there is no evidence that he actually built or tested such a concept.



Fig. 22. Early Flapping Wing Concepts and

Karl Meerwein was the first to estimate the size of a wing surface necessary to support the weight of a man using as a basis the weight and corresponding wing area of birds. Taking the wild duck as his model, he found that a man, weighing 200 lbs. with the machine, would require a surface of 126 sq. ft. His apparatus consisted of two light wooden frames covered with calico. The pilot was fastened in a horizontal position in the middle, with a balancing rod in front of him, which worked the strokes of the wings when pressed by the body. Meerwein apparently made one unsuccessful experiment in 1789.

Friedrich von Drieberg was the first to acknowledge that man has the greatest power in the muscles of the leg, and must use these for the movements of flight. Up until this time it was commonly assumed that the wings must necessarily be moved with the arms. Drieberg's concept consisted of a bat-like flying apparatus in which flight was to be obtained by flapping the wing by treading with the feet, while lying horizontally.

Edward Frost constructed an ornithopter made of willow, silk and feathers supported on a wooden frame. When his ornithcopter was suspended from a tree it was said that it would rise slightly with every beat of the wings. The entire contraption was much too heavy to ever fly. He built his last ornithcopter in 1904, a year after the Wright brothers first flew. Frost later became the president of the Royal Aeronautical Society.

The earliest known idea for flight with fixed wing geometry as in today's airplanes is the 1799 aircraft design by George Cayley which was sketched on a small coin. This concept is shown in the sketch in the upper left side of figure 23. Cayley's design had fixed wings for lift, a movable tail for control, and rows of "flappers" beneath the wings for thrust.

Pilcher built and tested a number of glider designs between 1895 and 1899 when after a structural failure; he was killed in the collapse of his last glider. His experiments provided a series of important results:

- Too much wing dihedral reduced stability in side winds.
- Too low center of gravity makes the apparatus very difficult to control.
- A flying machine can safely be raised by towing it against the wind like a kite.
- Light wheels at the front are convenient to move the machine about and to absorb shocks in landing.



Le Bris Albatross, 1868

Fig. 23. Early Fixed Wing Concepts and Vehicles

Alphonse Penaud in 1871 built a planophore, a 20-inch long monoplane with a pusher propeller powered by a rubber band. It flew 131 feet in 11 seconds becoming the first flight of an inherently stable aircraft. In 1874 Bishop Milton Wright bought one of Pénaud's toy helicopters. He took it home to his boys, Orville and Wilbur and, right there, Pénaud ultimately changed the course of history. While many of the early glider concepts were dangerous exercises of futility, others begin to add to the accumulation of knowledge of the critical elements for successful flight.

Le Bris built a glider shown in the lower right of figure 23, which was inspired by the shape of the Albatross. The glider consisted of a wood frame and was covered in cloth. The pilot (Le Bris) sat inside, almost like in a canoe, and used levers to operate the movements of the wings and tail. This invention which he patented in 1857, was the first flight control concept. In 1856 he briefly "flew" the glider was put on top of a cart which was attached to a horse that ran against the wind. At this point, the Artificial Albatross was released from the cart and began to rise into the air. The Albatross glider became the first ever to be photographed, albeit on the ground, by Nadar in 1868.

Chanute after experimenting with various mono-wing gliders, started to experiment with various multi wing concepts as shown in figure 24. The concepts were initially based on kite designs that exhibited stable flight characteristics. He ultimately ended up with his biplane box-wing concept shown in the right side of the figure. Chanute in time became a mentor to the Wright brothers. The wing planform geometry which the Wright brothers choose for their gliders and also for the Wright flyer was very similar to Chanute's double decker box wing shown in the right of figure 24.



Fig. 24. Multi-Wing Gliders - For Better Stability (Safer)

The imaginations of the early aircraft designers were almost unlimited in scope. These early aviation pioneers studied the flight characteristics of every conceivable type of flying animal-birds, insects, bats, flying fish, even flying foxes. Figure 25 shows the Avion III which was designed in 1897 and modeled after the geometry of a bat.



Figure 25: Early Inspiration from a Bat

The Avion III (Éole III) was a primitive steam-powered aircraft built by Clément Ader between 1892 and 1897, financed by the French War Office. This aircraft retained the same basic bat-like configuration of an earlier aircraft, the Éole. The Avion III was equipped with two engines driving two propellers. The propellers actually had a feather like structure. The Avion was equipped with a small rudder as means of directional control. Trials of the aircraft began at the Satory army base near Versailles on October 12, 1897, with the aircraft taxiing along a circular track. The first actual flight was attempted on October 14, 1897. The flight ended almost immediately in a crash without ever leaving the ground.

Date	Aviation Pioneer(s)	Event
1010	Oliver of Malmesbury Benedictine monk	Jumped from Malmesbury Abbey and became the first man to fly for some distance with the aid of wings.
1488-1514	Leonardo de Vinci	Made the first design of flying machines, using bird wings for models
1536	Denis Bolor (France)	Tried to fly using wings flapped by a spring mechanism. He fell to his death when the spring broke
1600s	Hezarfen Celebi	Leapt from a tower at Galata and flew some distance before landing safely
1799	Sir George Cayley	invented the concept of the fixed-wing aircraft
1804	Sir George Cayley	buillt and flew the world's first successful model glider
1868	Matthew Boulton	Obtained a British patent on a design for ailerons as control surfaces
1884	Horatio Phillips (England)	Designed a wing with a curved airfoil shape
1890	Clément Ader	flew a steam-powered, bat-winged monoplane, "the Eole", a distance of 50 m
1891 to 1896	Otto Lilienthal	Conducts over 2000 glider flights Before dying as a result of a crash
1896	Samuel P. Langley	Conducts the first reasonably large, steam-powered model aircraft flights of up to three quarters of a mile over the Potomac River
1900	Wright Brothers	Make their first glider flight

A summary of some aviation pioneering events prior to the first powered flight by man is shown in figure 26

Figure 26: Some Pioneering Events Prior to the First Powered Manned Flight

8. FLYING SEEDS

Dr. McMasters stated "*Plants mastered the art and science of aviation long before Orville and Wilbur Wright propelled their frail craft into the air*"⁸. This is evident in the concepts that nature has developed to enable seeds to navigate to suitable soil. If a tree dropped its seeds straight down, the seedlings would have to try to grow in the shade of the parent tree and would soon choke each other out. Seeds need to be carried away from its parent tree or plant and this now is accomplished in a variety of ways.

The most interesting aerodynamic example is probably the winged Zanonia macrocarpa seed shown in figure 27. This kidney-shaped seed comes from a large vine of the cucumber family. It grows in the dense, moist jungles of Indonesia

and has adapted its reproductive processes to a region in which there is no wind to distribute the seeds. The vine climbs 150-foot trees, and near the top, the Zanonia seed develops with two curved wings, transparent, gleaming, and very elastic. The seed-a kidney-shaped planform when released, begins its glide, rising on thermals from the jungle heat, and finally landing at a considerable distance from its point of departure. One professor described the Zanonia glider in this way: "*Circling widely, and gracefully rocking to and fro, the seed sinks slowly, almost unwillingly, to the earth. It needs only a breath of wind to make it rival the butterflies in flight.*" The Zanonia seed can perform amazingly long glides, during which it demonstrates basic inherent stability. Flights of up to 6 km from the vine have been recorded.

The aerodynamic features of the Zanonia macrocarpa seed include¹⁶:

- Swept wing and forward CG for longitudinal stability (reduce pitch-up tendency)
- Swept wing and reflexed trailing edge to avoid pitch-up
- Reflexed trailing edge to provide quicker stall recovery
- Drooped leading edge for higher CLmax
- Dihedral for roll and yaw stability
- Large aspect ratio = $3 \sim 4$ with a lift/drag ratio of 3 to 4
- Optimum center of gravity location for lowest rate of descent or highest duration of flight

A number of the early experimenters with tailless aircraft were inspired by the Zanonia's flying qualities. Igo Etrich adapted the principles he gleaned from his observation of the Zanonia seed to the design of his Leaf design in 1906. Rumpler developed his famous "dove utilizing a planform based on the Zanonia to which he added the "tail of a dove".



Figure 27: Early Innovation From a Seed

DiVinci utilized the concept of the spinning seed, shown in figure 28 to formulate his idea of the "air screw" which is considered to be the forefather of the autogiro, the helicopter as well as the propeller. Naturalist Christian de Launoy and his mechanic Bienvenu, about whom very little is known, developed a coaxial model of a simple helicopter powered by the tension in a bow. "When the bow has been bent by winding the cord, and the axle placed in the desired direction of height -- say vertically, for instance -- the machine is released," the pair told the French Academy of Sciences in 1784. "The unbending bow rotates rapidly, the upper wings one way and the lower wings the other way, these wings being arranged so that the horizontal percussions of the air neutralize each other, and the vertical percussions combine to raise the machine. It therefore rises and falls back afterward from its own weight." This concept was also the first counter-rotating propeller design.



Fig. 28. Spinning Seeds , Air Screws and Helicopters

A Large number of plants such as the dandelion use nature's version of the parachute to disperse their seeds as shown in figure 29. The very light seeds of the plant are attached to relatively large fluffy plumes that are released from the plant with a slight breeze. The high drag of the fluffy plumes results in very low sinking rates allowing the seeds to be blown and dispersed far from the plant¹⁶.

The first known written account of a parachute concept is contained in da Vinci's notebooks (cl495). The parachute concept that he conceived consisted of a cloth material pulled tightly over a rigid pyramidal structure. DaVinci never made nor tested his device. The first recorded successful test of such a parachute was made in 1595 in Venice by the inventor Fausto Veranzio who had examined Da Vinci's rough sketches of a parachute, and Fausto set out to implement a parachute of his own. Twenty years later, he implemented his design and tested the parachute by jumping from a tower in Venice.

In World War I and World War II the classic parachute was widely used. During the early space projects¹⁷, Rogallo developed a single membrane flexible wing, known as the parawing. Large parawings were designed for recovery of reentry vehicles. The parawing parachute was designed for maximum lift as opposed to the maximum drag of conventional parachutes. The parafoil was invented in the middle 1960's by Domina Jalbert, a kite maker. The parafoil or ram-air parachute is a deformable airfoil that maintains its profile by trapping air between two rectangular shaped membranes, sewn together at the trailing edge and sides, but open at the leading edge. Several ribs are sewn to the inside of the upper and lower surfaces, maintaining an airfoil cross section in the spanwise direction.



Art Explosian 800.000: i0423135.jpg







DaVinci (circa 1480 – 1483) Credit: Meyer, J. "An Introduction to Deployable Recovery Systems", Sandia Report SAND85-1180, Aug 1985



Figure 29: Drifting Seeds and Parachutes

9. KNOWLEDGE, TECHNOLOGY AND TOOLS FOR THE WRIGHT FLYER

When the Wright Brothers set as a goal, the development of the first powered aircraft they initiated their process by a search for all available knowledge of prior attempts to fly. Wilbur wrote a letter to the Smithsonian Institution requesting information and publications about aeronautics. Drawing on the work of Sir George Cayley, Chanute, Lilienthal, Leonardo da Vinci, and Langley, they began their flight experiments that year. They also built a strong networking relationship with Chanute who "believing that the surest method is first to study past failures ---- made an investigation of the records of all the experiments, which had been tried during the last two or three hundred years, in the endeavor

to imitate the birds. This resulted in a number of technical articles which swelled into a book, in which the attempt was made to eliminate the causes of each failure; for up to that time there had been nothing but failures". Mr. Chanute in 1897 had published^{13, 14} what may be considered to have been the state of the art understanding of ten critical elements that he considered to be essential to achieve successful powered flight. The first six, Chanute stated that they are well in hand and understood.

- 1. THE SUPPORTING POWER AND RESISTANCE OF AIR (Ability to Predict Lift and Drag)
 - We are now enabled to calculate with some confidence the support (lift) which may be obtained by gliding at any given speed upon the air, and the power required to overcome the resistance (ie drag). (Based on empirical formulae of Duchemin and Langley's experiments)
 - More encouraging (lift) coefficients for concave surfaces have been obtained by Lilienthal in his experiments.

2. THE MOTOR, ITS CHARACTER AND ITS ENERGY.

- For the first time the realization of a sufficiently light motor for a dynamic flying machine seems to be within sight.
- It now seems probable that this will be accomplished with a petroleum engine.

3. THE INSTRUMENT FOR OBTAINING PROPULSION.

- All sorts of contrivances have been proposed; reaction jets of steam or of compressed air, the explosion of gunpowder or even nitro-glycerine, feathering paddle wheels of varied design, oscillating fins acting like the tails of fishes, flapping elastic wings like the pinions of birds, and the rotating screw.
- Mr. Maxim and Professor Langley have made many experiments to determine the best form, speed and pitch of the screw (propeller) to obtain thrust from the air, and have materially improved that instrument,
- The Screw (propeller) seems likely to be the best device.

4. THE FORM AND KIND OF THE APPARATUS.

- Almost numberless projects have been advanced, but they can all be classified under three heads.
 - Wings to sustain and propel. (Ornithopters)
 - Rotating screws to lift and propel, (Helicopters)
 - o aeroplanes, to consist of fixed surfaces driven by some kind of propelling instrument.
- The first two have been the first to be proposed and experimented with. They have many warm advocates at the present time,
- Practical experiments made within the last five years seem to indicate that success will first be achieved with aeroplanes,

5. *THE EXTENT OF THE SUSTAINING SURFACES*. (ie. what is the required wing area?)

- The problem, relating to the extent of surface required to support the weight of a man, has caused in the past active controversy and gathering of data.
- It was perceived that in consequence of the law inherent to solids, the surfaces will increase as the squares, and the weights as the cubes of the homologous dimensions; it might well be that the additional relative weight due to the greater leverage should make it impossible to compass any larger flying machine than existing birds.
- The experiments of Lilienthal, demonstrated that a man's weight can be well sustained, at 22 to 25 miles an hour, by an apparatus with an area /weight ratio ∼ 1.25
- This apparatus need not weigh more than from 23 to 36 pounds, without motor or propeller, so that if the latter weigh some 60 pounds more, --- carrying a man of about 150 pounds, upon sustaining surfaces of approximately 200 square feet in area. (W/S ~ 1.25)

6. THE MATERIAL AND TEXTURE OF THE APPARATUS.

• The sixth question relates to the material to be selected for the framing of the machine, for the motor, and to the texture of the sustaining surfaces. Nature accomplishes her purposes with bone, flesh and feathers, but man has at his command metals, fuel and textile fabrics

• For a beginning wooden frames covered with textile fabrics will answer for a beginning.

7. THE MAINTENANCE OF THE EQUILIBRIUM.

- The seventh problem relates to the stability of the apparatus in the air, and especially in a wind.
- This equilibrium must be maintained at all angles of incidence and under all conditions of flight.
- Until automatic equilibrium is secured, and safety is ensured thereby, under all circumstances, it will be exceedingly dangerous to proceed to apply a motor and a propeller.
- Man will have to work out this problem thoroughly, if he is ever to make his way safely upon the air.
- 8. THE GUIDANCE IN ANY DESIRED DIRECTION. (Control Capability)
 - The eighth problem relates to the steering. It has been generally supposed that this would be best effected by horizontal and vertical rudders,
 - The experiments of Lilienthal, have shown that slight changes in the position of the center of gravity are immediate and effective.
 - It might be preferable to provide moving mechanism within the apparatus itself, to shift the surfaces so as to bring back the varying center of pressure over a fixed center of gravity, and that in such care the operator need not move at all, except for the purpose of steering.
 - Two forms of apparatus have been evolved, each equipped with a different device, which are now believed to be materially safer than any heretofore produced.
 - This problem cannot be said to be fully worked out, but it is not that a good deal of experimenting will be required, and that such experiments will be fraught with danger.

9. THE STARTING UP UNDER ALL CONDITIONS. (Takeoff capability)

- A really adequate practical flying machine will have to possess the power of starting into the air under all conditions
- *Three principal methods have been experimented with:*
 - 1. By acquiring speed and momentum using such appliances as railway tracks
 - 2. Utilizing the force of the wing.
 - 3. By the reaction of rotating screws --- this will eventually supersede the two others.
- This problem is as yet unsolved.

10. THE ALIGHTING SAFELY ANYWHERE. (Landing Capability)

- Alighting safely anywhere is of vital consequence and is also an unsolved problem.
- *The best method proposed involves the selection of a smooth soft piece of ground and the alighting thereon at an acute angle.* (Smooth runway)
- It would be preferable ---- to imitate the maneuver of the bird who stops his headway by opening his wings wide, tilting back his body back and obtaining the utmost --- retardation from the air before alighting upon the ground.
- It would be preferable to utilize the reaction of a rotating screw to diminish the forward motion.
- [It is interesting to note that the recommendations proposed by Chanute are quite similar to present day landing configurations and procedures including high lift systems with extended leading and trailing edge flaps, spoilers and reverse thrust]

Chanute went on to say "These last two problems – the rising and alighting safely, without special preparation of the ground – seem very difficult and are probably the last of which will be worked out."

The general common "Expert" belief at the time when the Wright brothers started the pursuit of their dream was that powered manned flight was not possible. This is evident by the quotes below of key scientific experts of the day.

Distinguished scientist (1895): "artificial flying machine is impossible for three reasons:

- 1. Nature, with her utmost effort, had failed to produce a flying animal of more than fifty pounds in weight.
- 2. That the animal machine was far more effective than any that man may hope to make.
- 3. That the weight of any artificial flying machine could not be less, including fuel and engineer, than 300 or 400 pounds."

Lord Kelvin, Royal Society President, 1895 "Heavier-Than-Air Flying Machines are Impossible"

Simon Newcomb (1835-1909), astronomer, head of the U. S. Naval Observatory. "...no possible combination of known substances, known forms of machinery, and known forms of force, can be united in a practical machine by which man shall fly long distances through the air..."

Widely attributed to George W. Melville, chief engineer of the U.S. Navy, 1900 "If God had intended that man should fly, he would have given him wings."

Simon Newcomb, Canadian-born American astronomer, 1902 "Flight by machines heavier than air is unpractical and insignificant, if not utterly impossible."

Even Wilbur Wright had his moments of doubt: in 1901 "I said to my brother Orville that man would not fly for fifty years." Two years later we ourselves made flights".

In spite of this prevailing negative mental environment, the Wright brothers believed in their dream and in a short period of three years succeeded. Their accomplishment provides a vivid example of two powerful messages:

- 1. "Believe you can, or believe you can't, either way you will be right"
- 2. "If the dream is big enough the facts don't count"

This was the "current" technical knowledge base and expert advice that formed the understanding of flight dynamics upon which the Wright Brothers launched their systematic technology and experimental developments that in a relatively short period of time achieved a first time achievement, that many had thought to be impossible – manned powered flight, as shown by the timeline in figure 30. The configuration features and development process followed the ten critical issues and development guidelines defined by Chanute.



Figure 30: Wright Brothers Aircraft Development

In 1900, 1901, and 1902, Wilbur and Orville Wright, achieved a considerable advance over all previous flying results. They were bold enough to be the first to place a man prone upon a gliding machine, instead of upright (for safety in alighting), and they used wing surfaces twice the area which previous experimenters had found it practicable to handle in the wind.

Following their first glider in 1900, They discarded the tail, and substituted for it a hinged horizontal rudder at the front, which could easily be operated by the pilot while under way. Their theory was that the pilot should constantly balance and guide the machine by the action of the rudder, steering to the right or left by warping one wing or the other using light control strings leading to his hands. The control of the machine by the rudder in front was found to be even better than had been hoped, and the landings were safely made at speeds of 10.m. per second.

The experiments of 1902 marked another great advance and mark a decided advance in the techniques of flight¹⁴. The apparatus could now be controlled so well that Wright brothers deemed it safe to pass on to the construction of a full flying machine equipped with a motor and propeller. They faced another seemingly daunting obstacle; the necessary

lightweight engine did not exist. Consequently they designed and built the first lightweight aluminum engine. They also designed and built their own propeller. This was done in 1903, and on the 17th of December of that year, after many trials and modifications, they had the satisfaction of making four dynamic flights from level ground against a wind of 10 m. per second-the first flight being of about 12 seconds, and the last of 59 seconds, when 260 m. were covered at a height of about 2 m. from the ground.



Various sub-systems that made up the systems of systems design of the Wright Flyer are shown in Figure 31.

Fig. 31. Wright Brothers Flyer System of Systems

10. MORE EXPANDED VIEW OF THE EVOLUTION OF FLIGHT

The development of our flying vehicles dreams, visions, attempts and ultimate achievement were enabled by the progressive synergistic developments in aerodynamic concepts and tools and other critical technologies developments as shown in Figure 32.



Figure 32: History of Commercial Air Travel

The evolutionary events leading to manned flight occurred over thousands of years. For as long as man has harbored the desire to fly, many attempts were made to emulate the flight of birds initially by strapping on some apparatus that had some resemblance to a bird and then leaping off a tower or other high prominent location. This type of event was repeated over and over, but seldom by the same person. These Real Fluid Dynamics, RFD, experiments, which we will define as manned flight experiments, have occurred over thousands of years. Most of these early experiments failed, many of which suffered serious consequences. Lilienthal's and Chanute's numerous glider experiments represent the first extensive exploratory studies of manned flight.

The Fundamentals of Fluid/Flight Dynamics, FFD, equations were developed over a period of approximately a thousand years before the Wright Brothers. These include all the contributions by daVinci, Euler, Bernoulli, Navier-Stokes as well as boundary layer theory, the concept of circulation and linear theory formulations. However the ability to utilize these formulations awaited the development of the digital computer and consequently, had rather little significance in enabling early powered flight. Computational Fluid Dynamics, CFD, did not come into existence until about 1960. The impact of CFD, since that time, has become incredibly significant.

The earliest form of Experimental Fluid Dynamics, EFD, activities utilized whirling arm mechanisms. These did provide some basic understanding of lift and drag forces. The Wright Brothers built one of the first wind tunnels. Their experiments provided valuable information and data that were used to support their flight experiments. Two of the other critical enabling technologies in addition to the wind tunnel, included a fundamental understanding of Stability & control Flight Dynamics, SFD, and the development and flight validation of simple but effective control mechanisms. In addition, the Wright brothers built the first light weight aluminum engine which they used for the Wright Flyer of 1903. This development process leading to the first manned flight clearly illustrates a typical feature of the development of new technologies and concepts. This is the requirement to advance on many disciplinary or technical fronts.

Following the pioneering developments of the Wright Brothers, the demand soon arose for greater flight capabilities. The further development of the aerodynamic tools, together with the developments in other technologies, lead to dramatic increases in the performance and operational characteristics of aircraft.

The two most critical tools of the aerodynamicist, (KFD and UFD), are intimately related but fundamentally different. Knowledge of Fluid/Flight Dynamics is similar to a collection of pieces and perhaps partly assembled pieces of a great puzzle. The collection generally may be lacking some of the key pieces. In addition some of the pieces may be invalid or from a different puzzle. Our understanding, UFD, is the image that we create by assembling the pieces we have accumulated as well as inferring the nature of the missing pieces. Man's knowledge and understanding of the nature, of biomechanics of flight has evolved through the systematic development and utilization of the engineering tools and processes, as well as critical synergistic and enabling developments in many other technical disciplines. The expanded use of our tools have provided many additional pieces to out knowledge and understanding puzzle that are reflected in the increased capabilities and sophistication of our modern flight vehicles.

Figure 33 illustrates the paradigm shift in commercial aircraft design drivers from the earliest aircraft to the commercial aircraft of today¹⁸.



Fig. 33. Commercial Aircraft Design Drivers and Technology Focus

The designs of early propeller commercial aircraft were innovation driven with the primary goal of increasing aircraft performance. That is to *fly higher, faster* and farther as well as to become bigger.

The introduction of jet powered swept wing aircraft provided revolutionary increases in aircraft size, cruise speed, cruise altitude and range. The cruise speeds and altitudes have remained essentially constant for subsonic aircraft jet aircraft. The early jet aircraft designs were determined by the aircraft manufacturer with inputs from the airline customers. Technology advancements were focused on increased *functionalities* including aircraft growth capabilities, operating economics and range.

The designs of the third generation of commercial aircraft were increasingly driven by customer inputs with supplier options and the areas of technology development were focused on various *efficiencies* including family growth concepts, improved economics, increased range and aircraft noise reduction.

The new generations of commercial aircraft designs will be both customer and society driven. The manufacturer will provide design options determined by strategic assessments of economic risks and opportunities. The technology focus areas will include in addition to those of previous aircraft, more efficient manufacturing processes, fuel efficiency and reduced emissions, travel time and affordability, safety and security, and improvements in the ATM system. Because of the highly competitive nature of today's market place, one of the primary goals of new aircraft is that of basic company *survival*. Unless a new airplane is the best offering to the airlines, lack of sales could force a company out of business.

If we compare the technology drivers of nature (figure 10) with the technology drivers for commercial aircraft (figure 33) we arrive at the observation shown in figure 34.

The evolutionary driver for nature's flyers was initially survival, and then gradually progressed through stages of efficiency, functionally and ultimately higher, faster and farther. The technical driver for manned commercial flight, however, appears to have progressed in the opposite order. I am not sure if this is biologically accurate, but it is an interesting observation.



Fig. 34. Why Did Flight Evolve? - : Contrasting Technology Development Drivers

11. OPPORTUNITIES AND NEEDS FOR INNOVATION

"The Rapid Journey From the First Tentative Flights to the Modern Airliner is a Testament to the restless search for technological improvement that has long characterized the aircraft business.¹⁹". This rapid journey is evident in dramatic change in aircraft configurations as shown in figure 35. Forty six years after the feeble but historically

significant flight of the Wright Brothers, the sleek, swept wing jet powered B47 flew. Forty six years later the B777 made its debut in the commercial transport arena.



Fig. 35 The Rapid Technical Growth of Aircraft

"The Rapid Journey From the First Tentative Flights to the Modern Airliner is a Testament to the restless search for technological improvement that has long characterized the aircraft business²⁰." The high degree of design sophistication of the modern aircraft can be seen by the areas defined by CFD and multi-disciplinary design and optimization techniques ²¹ in the B787 as shown in figure 36, and by the advanced design and operating features of modern military aircraft as shown in Figure 37.



Fig. 36. CFD contributions to the 787

- STOL / VTOL Capabilities
- Long Range
- Extender Loiter
- Highly Maneuverable
- Minimum Energy Requirements
- Minimized Noise and Stealth Features
- Morphing Wing and Control Surfaces





Fig. 37. Aircraft Multi-Mission Advanced Technology Concepts

Aerodynamics together with structural and manufacturing considerations largely define an airplanes exterior contours. The technological progress in aeronautics is often associated with size and shape of the aircraft. It can be argued with some degree of validity, that the vast majority of existing aircraft were established approximately 65 to 70 years ago²². Ingo Rechenberg²³ said that he finds it "very remarkable that after 100 years development a modern aircraft still looks like a bird: a spindle body, the wing in front and the elevator behind. That's the solution of biological evolution and that's still the basic concept of a modern aircraft." However this certainly does not mean that man has exhausted all possible aircraft related innovative or creative technology developments.

The needs for continued technical innovation and development for aircraft far exceeds just the external shape or operating procedures. The needs for technical innovation permeate every element of the systems of system. Some of the general critical areas for which technology developments are in need commercial air transportation include:

- · Factors that affect the costs to build, own, operate and maintain a commercial aircraft
- Aircraft community noise reduction
- Design and Manufacturing Processes, (Cost to Build)
- Emissions / Fuel Efficiency
- Travel Affordability / Time / Comfort
- Safety / Security
- Air Traffic Management

Where do we go from here in the next 100 (or even 20) years? There are at least three possible answers, as shown in figure 38 all of which are likely one way or another:

- Keep running harder and harder (i.e. doing what we have been doing) to develop innovation solutions for today's classes of aircraft.
- Schedule a breakthrough (e.g. a possible Sonic Cruiser II via large reductions in sonic boom intensity and "aerospace plane" technology) or an invention (e.g. economically and logistically viable alternatives to fossil fuel propulsion schemes for transport aircraft).
- Start a whole new game one in which the gap between the possible and the achieved is once again very large, e.g. the whole range of possibilities for uninhabited [combat] air vehicles (UAV/UCAV) type vehicles, which represent a complete fusion of traditional and emergent aerospace vehicle technology with "information and communications technology."



Fig.38. Aircraft Future Technology Needs and Opportunities

A general characteristic of technology development is the need to advance the technology on all fronts. Consequently each and every component technology or systems development becomes a critical element in the overall innovative development processes. With our view of an aircraft as an integrated system of systems, this implies that a technology development in one system no matter how seemingly small or unrelated can become an important element in the overall system development. Consequently one should be open beyond their immediate technical discipline to any concept that offers potential improvements for the system as a whole.

12. TECHNOLOGY DEVELOPMENT STRATEGIES

The development or "evolution" of aircraft technology has many apparent parallels with the evolutionary processes of nature even though as previously discussed evolution, and the development of technology are fundamental different.

Coevolution is a major driving force for technology developments especially if we consider in addition to the aircraft manufacturers, such elements as the propulsion manufacturers, the competition, the users, the operational facilities and environments.

- "Competition" between different manufactures to produce the "best" overall aircraft favored by the customers and users.
- Predator vs prey for military defensive and offensive developments, and for detection and evasion developments.
- "Mutualism" between aircraft operations and airports
- Mutualistic developments between airframe manufactures relative to safety, security, environmental concerns and airspace management.
- Special interiors for airlines are an example of a commensalism symbiotic coevolutionary relationship between the manufacturer and the airlines.

The evolution of technology is somewhat related to the Lamarckian theory of evolution which assumed that new traits were acquired by need and usage and these new traits are passed on to subsequent generations as long as they were used. New technology developments are driven by need and these developments will indeed be passed on to subsequent generations as long as the technology is used.

Figure 39 shows the timing and value creation of the four major stages of the development of a new technology



Fig. 39. Aircraft Technology Development Stages

Figure 40 shows the historic "discovery" driven (push) technology development process. The discovery driven development process is a creativity based approach that is initiated with new or existing conceptual ideas



Fig. 40. Historic "Discovery" Driven Technology Development Strategy

Based on either a new or existing unique conceptual idea, a research activity may be started to develop this technology. The initial activity focus is on developing a fundamental understanding of the new concept or method. Allowances are made to permit exploring and determining any key or critical parameters associated with the concept. The research activities include developing the necessary databases required to validate the concept or method and to seek out the necessary supporting technologies.

The available resources for such a program are seldom fixed. The development time is consequently greatly dependent on the outside interest and the level of funding. In today's research environment, funds to carry on such research are extremely difficult or impossible to find. If the research program is successful and a product is proven and available there comes the search for a customer. Often the technology may wait years for a need finally emerges.

This historic process has lost favor to the present day application driven strategy. Major advantages of the historic process include:

- Allows Relatively Unconstrained Creative Thinking
- Source of Almost All Aerodynamic Innovations and Advanced Technologies
- Best Approach for Conceiving New Technologies

The major disadvantages for this approach include:

- May lead to unused innovations -no customer(s)
- Difficult or impossible to schedule for near term applications
- Long time to market
- Today is it is difficult to obtain either industry or Government funding

Some examples of aerodynamic technologies developed by this process include:

- NACA Airfoils and Cowl Shapes
- Supercritical Airfoils
- Swept Wings
- Natural Laminar Flow Applications
- Laminar Flow Control
- Hybrid Laminar Flow Control
- Original Supersonic Design and Analysis Methods
- Skin Friction Prediction Methods
- Supersonic Area Rule
- Supersonic Nacelle / Airframe Integration
- Most CFD Codes (Full Potential, Euler, Navier Stokes)
- Swept wing
- Delta Wing
- Arrow Wing
- Variable Sweep Wing
- Variable Sweep Oblique Wing
- Turbulent Flow Viscous Drag Reduction concepts (eg Riblets)
- Sonic Boom Prediction and Design Methods
- CFD turbulence models

The following is a quote from the Strategic Plan, Defense Advanced Research Projects Agency, DARPA, February 2003 "None of the most important military developments of the 20th century – the airplane, tank, radar, jet engine, helicopter, electronic computer, stealth, internet technologies. - not even the atomic bomb – owed its initial development to a doctrinal requirement or request of the military. None of them. "

The current technology development model is "product" driven and is often called the technology "pull" method is shown in figure 41.



Fig.41. Current "Product" Led Technology Development Process

The product driven technology driven approach is launched to fulfill some specific need(s) of a customer or airplane program. The requirements for the technology are known. The resources including both time and funds are specified and development funds are available.

The technology phase will basically apply existing ideas or concepts of which the designers are aware. The activity focus will be heavily guided by the product design objectives and timing requirements.

This method of technology development seems best for advancing a known concept or methodology.

The major advantages of this development process include:

- Best Approach for Adapting or Improving a Technology Concept
- Customer for the Technology is Known
- Focused Activity for Defined Development time
- Short Time to Market
- Current Approach Required For NASA / Industry Funding

The major disadvantages include:

- Seldom Allows Innovative or Creative Thinking
- Cannot "Schedule" Invention
- Few if Any Innovative Technologies Conceived by this Approach
- Focus is usually on "results" and not on "Understanding"
- Usually focused on near term applications

Examples of aerodynamic technologies advanced by this process.

- Low Sonic Boom Configurations
- Non-Linear Aerodynamic Design Optimization
- HLFC Application Assessments
- Slotted Wing Development
- Application Driven CFD Developments

A.D Welliver, Boeing former Senior Vice President said²⁴ "In short, technical excellence is essential. but it isn't worth much if it doesn't find its way properly into the product and then prove useful." John Rennie in a 1995 Scientific American article²⁵ stated "The abstract quality of an innovation matters not at all. A good technology must by definition be useful. To survive, a commercial technology must not only work well, it must compete in the marketplace."

Figure 42 shows the integrated activities of the universities, the Government research laboratories and industry technology development activities in the previously discussed technology development models along with a recommend integrated technology model. In all three models, the Universities activities are primarily in basic research. In the discovery technology development model, both industry and the Government research labs are also actively involved in basic research.

In the product focused technology development strategy. Industry is no longer actively involved in either basic or applied research. The government research labs involvement is also reduced primarily to the role of funding cooperative programs. Thus the number of participants involved in basic research has been greatly reduced. This also means that the numbers of jobs available for university graduates who wish to continue their research work beyond their doctoral programs are also greatly reduced. It is also felt that other adverse effect of this development approach includes:

- The universities research programs may not be properly aligned with industries greatest needs
- Industry may not be fully aware of the universities research that might be applicable for a new airplane program.

In either of the above development strategies, the development time from basic research to application readiness is rather long. The recommended technology development model would have the Government labs to once again become very actively involved in basic research. In addition, the government research labs would also focus on accelerating the development of the most promising new technologies. Industry would once again be committed to basic research but in slightly different roles. Industry would provide some opportunities for their technology specialists to development network relationships with the researchers in the universities and the government labs to become more aware of future technology developments that might be applicable to new program developments, and also it help insure that the universities and the Government labs are indeed aware of industries most pressing needs.



Fig.42. Integrated Aircraft Technology Development System Options

13. SIMILARITY ANALYSES AND ALLOMETRIC SCALING STUDIES OF NATURE

Modern birds fully and elegantly embody a number of items that have been the subject of much research and development in aviation in recent decades. These items include mission adaptive wings of extreme sophistication, an advanced high-lift system, an active flight critical control system, a self-repairing/self reproducing composite structure, and fully integrated system architecture. There are many other technical areas of potential importance that are well demonstrated in natural flying devices such as the various uses of vortices for flow control, and the problems and benefits of controlled large-scale unsteady separated aerodynamic flows. We obviously have much to learn from the masters of flight as shown in figure 43.



Fig. 43. Important Aeronautical Technology Incorporated In Birds

"Living organisms are examples of design strictly for function, the product of blind evolutionary forces rather than conscious thought, yet far excelling the products of engineering. When a designer looks at nature he sees familiar principles of design being followed, often in surprising and elegant ways. Sometimes, as in the case of flight, he is inspired to invention: more commonly, he discovers his ideas embodied in some animal or plant²⁶."

Professor Robert J. Full, of the University of California, Department of Integrated Biology has suggested "Do NOT Mimic Nature - Be INSPIRED by BIOLOGY and use these novel principles with the best engineering solutions to make something better than nature." Following that wise advice, we will therefore explore a number of biologically related approaches for potential technical inspirations and design innovation. These will include:

- Bionics: Visual Inspiration from the shapes, designs and movements found in nature
- Biomimicry: Conceptual Inspiration by utilization of forms or concepts for diverse applications resulting from improved understanding of the processes occurring in Nature.
- Neo-Bionics: Computational Inspiration utilizing numerical optimization techniques that emulate nature's selection and optimization processes and strategies.
- Cybernetics: Inspiration obtained by reverse engineering of natures "designs" Inspiration by Natures Things
- · Pseudo-Mimicry: Inspirational designs confirmed by nature designs and solutions
- Non-Bionic: Inspiration obtained independent of nature's designs Inspiration by Other Things..

To be inspired by nature it is important to understand how nature creations are affected by size, environmental and operational effects. A good place to gain such an understanding is through the application dimensional analyses and simple similarity principles. Being able to develop a fundamental understanding of nature and also of physics is an essential element for identifying and / or conceiving innovative technology or design concepts.

Figure 44 contains the dimensions of various physical quantities in the Mass–Length–Time system, MLT. The physical quantities are also shown in a physiological system^{27, 28} based on a characteristic length, L. The physiological dimensions are useful for exploring the effects of size changes on characteristic shapes and performance limits. The appropriate selection of a characteristic length can be rather ambiguous. Most often, therefore, the body mass of an organism is used as the reference index for the correlation of morphological and physiological characteristics, especially when attempting to compare similar but different creatures.

Huxley's allometric equation $(Y = aM^b)$ is often used to mathematically describe the variation of various morphological and physiological characteristics with mass. This is the most simple and at the same time, the most versatile mathematical expression for intra- or interspecies comparisons. The exponents (b) for the allometric equations can be predicted for all biological variables definable in terms of the MLT system of physics (M = mass, L = length, T = time). The exponents can often be estimated by means of dimensional analysis using appropriate similarity criteria such as: a) geometric similarity, b) mechanical or dynamic similarity, b) kinematic or biological similarity; elastic similarity. The scaling coefficient "a" is generally determined by statistical analyses of existing appropriate data sets.

Using the mass based physiological dimensions we can identify simple relations that can provide answers to interesting questions about nature such as shown in figure 44.

Quantity	Dimensions		Physiological	
Quantity	Physical	Physiological	Mass Based	
Length	L	L	M 1/3	
Mass	М	L ³	М	
Time	t	L	M 1/3	
Cross Section Area	L ²	L ²	M ^{2/3}	
Surface Area	L ²	L ²	M 2/3	
Volume	L3	L ³	М	
Velocity	Lt ¹	L ^o	M ^o	
Frequency	t ¹	L ⁻¹	M -1/3	
Acceleration	Lt ²	L ⁻¹	M -1/3	
Force	LMt ⁻²	L ²	M ^{2/3}	
Impulse	LMt ⁻¹	L ³	М	
Energy	L ² Mt ⁻²	L ³	М	
Power	L ² Mt ⁻³	L ²	M 2/3	

 Smallest Birds and Biggest Birds
 "Eat like a Bird → A Little or a Lot?
• Why do Little Birds with Big Eyes Sing Early
in the Morning?
 Why no Small Mamuals in the Sea?
How Tall Can A Tree be?
 Why Can a Whale be so Big?
 If a Flea Was as Big as a Man, Could it
Really Jump Over the Space Needle?
 How is a Flea Like a Compound Bow?
 Why do Mosquitoes "Come Out" at Night?

Reference for discussion J.C. Georgian, The Temperature Scale, Nature, 201-595, 1964 Figure 44: Dimensional Analysis, Similarity and Insight into Nature

Birds are warm blooded animals and must maintain essentially a constant internal temperature. Heat loss for an animal is proportional to the surface area. The heat generating capability is proportional to the mass of the animal. Using the physiological mass based relations shown in figure 44, the relative heat loss to heat generation ratio is therefore proportional to $(Mass)^{-1/3}$. Smaller animals therefore, have an increasingly difficult task to maintain a constant internal body temperature. This limits the smallest size for a bird which is the male bee hummingbird that lives in Cuba. It weighs 0.056 ounces and is about 2.75 inches in length. The bill and tail account for half of its length. The smallest bat is the bumble bat which weighs less than a penny and when full grown is about 0.433 inches in length. The White-toothed Pygmy Shrew is the smallest known mammal by mass, weighing only about .05 oz and is about 1.43 inches long. Because of their tremendous metabolic requirements the tiny hummingbirds, bats and mammals must eat a large amount of food equivalent to the average human consuming an entire refrigerator full of food. Hummingbirds eat roughly twice to three times their own body weight in flower nectar and tiny insects each day. Consequently, if someone says "*you eat like a bird*", it should not be taken as a compliment. For the same temperature loss reasons there are no small mammals in the sea. The heat loss is even greater because of the cold water in the oceans. Little birds as previously mentioned, require a large of nourishment daily. Having large eyes enables a bird to start its search for food very early in the morning. Therefore, little birds with big eyes sing early in the morning.

The square/cube law can also be used to explain the limit to the greatest height of a tree. The bending strength of a tree is proportional to its cross section area. The mass of the tree is proportional to the cube of its linear dimension. Consequently tall tree experience greater stresses during a wind storm. This ultimately limits the height of a tree. Whales do not have to structurally support their own weight because of the buoyancy effect in the water. Therefore whales can be many times larger than the largest land mammal.

Fleas can normally jump about 100 to 200 times their own height. If a flea was as tall as a man, could it really jump over the space needle? We can answer this using the above physiological mass based parameters. The maximum height of a jumping object is related to the liftoff velocity. For a standing high, the liftoff velocity, ΔV , times the mass equals the jumping impulse. Impulse as shown in figure 44 varies directly with mass. Therefore as shown in equation 1, the lift off velocity is independent of the size of mass of the jumper. Consequently, all things independent of their size jump about the same height²⁹.

$$Impulse = M * DV \rightarrow \Delta V \sim M^0$$
(1)

The bar chart shown in figure shows that the froghopper, locust and man each do a maximum standing high jump to about the same maximum height even the mass between the jumpers varies by nearly a factor of a million. The jumping height of the man is defined by how high the center of gravity moves from lift off to the peak height. The click beetle jumps less that the others since it jumps while lying on its back.



Fig. 45. If a Flea Were as Big as a Man -----

A small creature is actually handicapped by its size. The ballistic coefficient (BC) of a body, which is a measure of its ability to overcome drag in flight, is proportional to mass divided by area and therefore varies with $M^{1/3}$. Therefore, a small creature is affected more by drag during the jump trajectory.

The jumping impulse is actually achieved by a finite acceleration, "Aj" acting for a finite time "Tj". Impulse = Aj \cdot Tj As shown in the table acceleration varies with M^{-1/3} and the time varies with M^{1/3}. Consequently for a very small creature such as a flea, the necessary acceleration becomes extremely large and well beyond the capability provided by the lever / muscle jumping system utilized by man. The required jumping acceleration is shown in figure 46. The jumping acceleration for a man is about 1.75 g whereas for a flea size creature, the required jumping acceleration is about 500g.

Froghopper Jumping



Used With Permission: Professor M. Burrows, Department of Zoology, University of Cambridge



Fig. 46. Jumping Accelerations of Fleas, Froghoppers and Man

Animal	Wt, Ibs		
Indian Elephant	9000	10000	
White rhinoceros	6000	8000	
Hippopotamus	3000	4000	
Giraffe	2900	3800	
Asian gaur	2200	3300	
Yak	1800	2500	
Bison	1800	2200	
Brahman Bull	1600	2200	
Moose	1100	1580	
Standing High Jump Limit (1.5 to 1.3 g)	900	1400	
horse	1000	1300	
Elk	700	1300	
male lion	350	400	
whitetail deer	150	250	
Eastern Grey kangaroo	40	200	

Fig. 47.Weight Range of Various Mammals

The muscles of a flea are simply not powerful enough to do this. Consequently the actual jumping performance of a flea would be very poor if it were not for the specialized design of its legs provided by nature. A flea jumps by releasing energy that it has stored in its muscular springs. These springs are loaded relatively slowly (about 50 milliseconds) by means of muscles and then released suddenly (1 millisecond). The flea stores the energy by an "over the top dead center" so that the muscles that load the jumping "springs" can relax and not have to work to retain the stored energy²⁶.

This is very similar to the mechanism of a zero holding weight compound bow. The archer converts chemical energy in his muscles to potential energy elastic energy in the limbs of the bow, by drawing the bow string back. The stored potential energy is indicated by the gray area in the figure. By proper design of the cams on the bow, the force requires to hold the string back at its design condition can be very small or even zero force. Releasing the bow string converts the stored potential energy into the kinetic energy of the arrow. In a similar manner, the flea can convert its stored potential energy into its jumping kinetic energy. A sequence of jumping pictures of a froghopper³⁰ is shown in figure 46. The jumping acceleration data and pictures for the froghoppers were obtained from the extensive studies of Professor Burrows and his colleagues in the Department of Zoology at the University of Cambridge³⁰.

If we assume that a minimum acceleration for jumping would be 1.5g to 1.3g, we can then use the allometric acceleration curve to estimate the maximum weight of an animal that can make a standing high jump. The maximum jumping weight would be about 900 to 1400 pounds as shown in figure 47.

Professor Heitler and his colleagues at the School of Biology at the University of St. Andrews, Scotland have conducted extensive studies³¹ to understand the jumping mechanisms of the grasshopper which includes a combination of the spring mechanism of the flea and the leverage system of a man. Figure 46 contains a sequence of pictures of a jumping grasshopper. The contraction / spring loading process followed by an instantaneous release are also shown in the figure.



Credit: With Permission, Heitler, W.J., School of Biology, University of St. Andrews, Scotland, UK.



Credit: Malc Burrows of Cambridge University, Credit: With Permission, Heitler, W.J., School of Biology, University of St. Andrews, Scotland, UK.

Fig. 48. Jumping Mechanism of a Grasshopper

Figure 49 shows some comparative measurements for a number of birds and insects²⁹. The physiological mass based dimensions are also shown for the various quantities in the lower row of the figure. The physiological mass based dimensions can be used to explain the size related effects on the performance of birds and insects.

	Weight gm.	Length of Wing m.	Beats per Sec.	WING Tip Speed m/s	Force of Wing Beat gm.	Specific Force F/W
Stork	3500	0.91	2	5.7	1480	0.40
GULL	1000	0.60	3	5.7	640	0.667
Pigeon	350	0.30	6	5.7	160	0.50
Sparrow	30	0.11	13	4.5	13	0.40
Bee	0.07	0.01	200	6.3	0.2	3.50
Fly	0.01	0.007	190	4.2	0.04	4.00
Physiological Dimensions	≈ M	≈ M ^{1/3}	≈ <mark>M</mark> -1/3	Mo	М	Mo



Fig. 49. Size Effects on Natures Flyers

Fig. 50. Jumping Liftoff of a Crow

The wing span is seem to vary approximately with the scaling factor $M^{1/3}$. Periodic events repeat themselves after a time T. For biological periodic motions the time scale is proportional to the $M^{1/3}$. Wing beat frequency with units of 1/sec has physiological dimensions proportional to $M^{-1/3}$. The wing beat frequency increases greatly for small birds and insects. The wing tip speed which is equal to the product of wing semi-span times the rotation frequency as shown by the physiological mass parameter is essentially constant of all of the birds and insects. The force that a bird can exert is proportional to its weight. The specific force which is the ratio of the force to weight is therefore independent of the size of birds. The same is true for insects. The thrust to weight ratio for birds is however less than one. This means that birds, with the exception of the hummingbird cannot just lift off from a surface. They must either squat and then jump to get airborne, propel themselves from some high object or run along the ground or water to gain enough speed to begin to fly. Insects, on the other hand, have thrust to weight ratios much larger than one and can therefore fly directly off a surface. The sequence of pictures in figure 50, show a crow first crouching and then leaping up to get airborne as it starts to flap its wings.

Let us now develop a relationship between the cruising speed and the weight of insects, birds and airplanes. Using the definition of lift coefficient as derived from dimensional analysis, wing loading (weight/wing area) is proportional to velocity squared: $W/S \sim V^2$. From the previously discussed similarity relations, wing loading is proportional to weight to the 1/3 power: $W/S \sim W^{1/3}$. Consequently, this implies that the cruising speed varies with weight to the 1/6 power: $V \sim W^{1/6}$. Figure 51 shows a correlation of the flight speeds of tiny insects through massive transport airplanes with this simple velocity versus weight relation. There are twelve orders of magnitudes of weight variation (Newtons) from the tiny insects to the large transport aircraft and there is slightly more that two orders of cruise speed variation (meters/sec.).



Fig. 51. Cruise Speeds for Insects, Birds and Airplanes

Cruising speeds of some of nature's flyers are compared with various wind conditions in figure 52. The cruise speed must exceed the wind speed in order to make any progress. Mosquitoes and gnats will only fly in light breeze conditions. Since these light breeze conditions generally occur in the evening, "mosquitoes only come out at night".

Wind, mph	Beaufort Number	Wind	Weather	Natures Cruise Speeds, mph
1-3	1	Light Air	Wind motion visible in smoke.	Butterflys
4-7	2	Light Breeze	Wind felt on exposed skin. Leaves rustle.	Gnats, Midges, Danselflies, Mosquitoes
8 -12	3	Gentle Breeze	Leaves and smaller twigs in constant motion.	Human Powered Aircraft, Flies, Dragonflies
13 -18	4	Moderate Breeze	Dust and loose paper raised. Small branches begin to move.	Bees, Wsps, Beetles, Hummingbirds, Swallows
19 - 24	5	Fresh Breeze	Branches of a moderate size move. Small trees begin to sway	Sparrows, Thrushes, Finches, Owls, Buzzards
25 - 31	6	Strong Breeze	Large branches in motion. Whistling heard in overhead wires. Umbrella use becomes difficult. Empty plastic garbage cans tip over.	Blackbirds, Crows
32 - 38	7	Moderate Gale	Whole trees in motion. Effort needed to walk against the wind. Swaying of skyscrapers may be felt on upper floors.	Gulls, Falcons
39 - 46	8	Fresh Gale	Twigs broken from trees. Cars veer on road.	Ducks, Geese
47-54	9	Strong Gale	Larger branches break off trees, and some small trees blow over. Construction/temporary signs and barricades blow over.	Swans, Coots
55 - 63	10	Whole Gale	Trees are broken off or uprooted, saplings bent and deformed, poorly attached asphalt shingles and shingles in poor condition peel off roofs	Sailplanes
64 - 72	11	Storm Winds	Widespread vegetation damage. More damage to most roofing surfaces, asphalt tiles may break away completely.	Light Aircraft
> 73	12	Hurricane Force	Considerable damage to vegetation, a few windows broken, structural damage to mobile homes. Debris may be hurled about.	

Fig. 52. Natures Cruising Speeds and Wind Conditions

We can use similarity relations to establish the approximate largest size for a flying bird 32 . As shown in figure 53, there is a strong correlation between flight muscle mass (and thus power available) and total mass of most birds. The power required to fly is proportional to cruise drag times velocity. The drag which is proportional to velocity squared times area and therefore varies directly with mass. The product of drag times velocity therefore varies as $M^{7/6}$.

In figure 54 the power available and the power required values for a pigeon are extrapolated using the above relationships. If the available power is less than that required for flapping flight at a particular speed, then flight is simply not possible. If it exceeds the power required, then the excess power can be used for other demanding tasks such as maneuvering or climbing flight. Using the known data for a pigeon as an anchor, we can project the curves to the point where power available exactly equals the power required. The results indicate that the maximum mass of a flying bird is about 20kg (44lbs). This is consistent with that of a barely able to fly South African turkey, the Kori bustard³².



Fig. 53. Flight Muscle (Power Available) vs Total Mass in Birds.

Fig. 54. Power Requirements for Steady, Level Flight

14. "BIONICS" AS A SOURCE FOR DESIGN INSPIRATION

Bionics can be formally defined as the science of copying nature for a similar application or engineering solution for the benefit of mankind. This includes copying nature designs, operating procedures and flow control mechanisms. D. J. Murray-Smith⁶ has said that "*Any engineer must inevitably have respect for the excellence of the design that can be seen in biological systems.*" The previously discussed Zanonia Macrocarpa flying seed (Figure 27) is considered to be the biological inspiration for the flying wing as shown in figure 55.



Figure 55: Zanonia Macrocarpa and the Evolution of the Flying Wing

Dr. Lippisch wrote, "*Nature had designed the flying wing thousands of years before man even thought of flight*". The flying wing was the Zanonia seed, a seed from a large vine of the cucumber family. Early aviation pioneers were impressed with the perfect flight of the Zanonia seed. In building craft light enough to soar in the wind, stability was the key. Lilienthal's glider of 1891 shows a distinct resemblance to the cucumber seed. The Horten Brothers and Northrop continued development of the flying wing in the 1940s. The early research together with numerous system technology developments ultimately led to the Northrop Grumman B-2 aircraft.

A recent bionic design example is the spiroid wing tip invented by Dr. Gratzer of Aviation Partners as shown in figure 54. This induced drag reducing innovative concept, was derived from the spread primary feathers of a large soaring type bird as shown in figure 56.



Fig. 56. Spiroid Wing Tip Bionic Innovation

Bionics studies on the aerodynamics of bird flight which were carried out by Dr. Bannasch of EvoLogics R&D Lab Bionics³³, his colleagues and industrial partners in collaboration with TU Berlin has yielded insights and new ideas on how to minimize vortex related drag associated with wing tips. The concept of a bionic wing tip was invented independently by Dr. Bannasch, figure 57. The extensive development of these ideas led to a novel shape for propellers, which has been patented worldwide as the Bionic Loop Propeller shown in figure 58.



Used with permission: Dr. Rydolf Bannasch, EvoLogics GmbH

Fig. 57. Independent Bionic Wing Tip Invention

Compared to regular propellers the bionic propeller sheds a continuous sheet of vorticity without core vorticies. Test results shown in figure 58 indicated that the bionic propeller increased power output from 20% to 50% and reduced the noise emission by $\frac{1}{2}$.



Fig. 58. Bionic Loop Propeller

Other bio-inspired investigations ³⁴⁻⁴⁰ have focused on efficient fuel saving flight techniques such as formation flying (figure 59). For nature's flyers utilizing these energy saving flight techniques may mean the difference between achieving their destination or by perishing along the way. There is some evidence that for large birds such as the Canadian goose, the maximum sustained power (aerobic) is often close or even less than the power required for flight. This implies that formation flight is not only a means to save energy and increase the flight range, but in some instances may be absolutely necessary even to fly at aerobic sustained power.



Fig. 59. Formation Flight

15. "BIOMIMICRY" AS A SOURCE FOR DESIGN INSPIRATION

Biomimicry can be defined as a science that studies nature's models and then imitates or takes inspirations from these designs and processes to solve human problems⁴¹. Phil Gates⁴² stated "Many of our best inventions are copied from other living things. We have discovered only a tiny fraction of the vast number of living organisms that share our planet. Somewhere, among the millions of organisms that remain undiscovered, there are natural inventions that could improve our lives." Biomimetics is an interdisciplinary subject which combines engineering science, architecture and mathematics. The basic principle is to make nature's problem solutions usable for man. The reason for this is very simple: Nature, through billions of years of trial and error, has produced effective solutions to innumerable complex real-world problems and nature has done a very good job. "Any engineer must inevitably have respect for the excellence of the design that can be seen in biological system"s⁴³.

The creation of Velcro is a classic example of Biomimicry. As the story goes, after taking his dog for a walk one day in the early 1940s, George de Mestral, a Swiss inventor, became curious about the seeds of the burdock plant that had attached themselves to his clothes and to the dog's fur. Under a microscope, he looked closely at the hook-and-loop system that the seeds use to hitchhike on passing animals aiding seed dispersal, and he realized that the same approach could be used to join other things together. The result was Velcro.

The Burdock plant is a group of biennial thistles. The prickly heads of these plants as shown in figure 60 consists of tiny hooks. These hooks are noted for easily catching on to fur and clothing, thus providing the Burdock plants an excellent mechanism for seed dispersal. The design that de Mestral developed as shown in the figure, emulates the hooks of the burdock thistle and the loops similar to those of wool.



Figure 60: The Burdock Plant and Velcro

The Velcro type of fasteners have found rather wide spread usage even within the aircraft industry such as:

- Lightweight, rustproof fasteners that do not rattle.
- A standard component in jet planes since the 1960s,
- Used on aircraft ranging from small Pipers to the Space Shuttle
- The fasteners used on the Symbion Total artificial heart
- Pallet tidy strap for pallet control/identification
- Fire Retardant hook and loop fastener.

Lotus Leaves

Velcro is an example of an "irritation" being a source of invention. Many of us have probably experienced walking through the woods and then returning with our socks full of burrs, a situation which most would categorize as a definite irritation. For most people, after the painstaking removal of the burrs, the situation is soon forgotten. De Mestral asked the question "why" then proceeded to answer the question and then found a way to exploit the answer. This is a good model for anyone to follow as a source for innovation.

In 1982 botanist Wilhelm Barthlott of the University of Bonn in Germany noticed that water when landing on a lotus leaf as shown in figure 61, formed spherical droplets that ran off the surface and in the process removed any dirt on the leaf. Upon further exploration he discovered in the lotus leaf a naturally self-cleaning, water-repellent surface. The secret lies in waxy microstructures and nanostructures that, by their contact angle with water, cause it to bead and roll away like mercury, gathering dirt as it goes. Barthlott patented his discovery, calling it the Lotus Effect. It has found commercial application in products like the biomimetic paint Lotusan (on blocks above). Infused with microbumps, the paint is reputed to repel water and resist stains for decades.

Drop of Water of a Lotus Leaf. Superhydrophobic Surface of a Lotus Leaf. Computer graphic of lotus leaf surface.





Photographer: Michael Gasperl (Migas)



Curiosity concerning how a duck (or seagull) could stand or swim in very cold water without its legs freezing led to the discovery that nature has developed in the spindly legs of a duck, a very efficient counterflow heat exchange system⁴⁴. Birds living in cold environments must conserve body heat in order to avoid hypothermia. However, blood flowing from the body core to the legs and feet carries heat that can be readily lost through the skin. To prevent such a loss, birds have evolved a counterflow heat exchanger system in their legs and feet as shown in figure 62. The blood vessels in the legs include arteries carrying warm blood down the legs to the feet, lie in close proximity to the veins carrying cold blood back from the feet. The cold blood in the veins gradually reduces the temperature of the blood in the arteries as it flows towards the feet. By the time the blood in the arteries reaches the feet it is nearly at ambient temperature which results in very little heat loss. In addition, the warm blood in the arteries heats up the blood returning from the feet in the veins so effectively that the return blood flow reenters the body of the seagull at essentially the internal body temperature. Consequently, even when a duck is standing in ice cold water, there is hardly any heat loss.

The principle of countercurrent heat exchange is so effective and ingenious that it has also been adapted in human engineering projects to avoid energy waste, e.g., by ensuring good ventilation of buildings while avoiding the loss of heat to the environment on a cold winter's day.



Fig. 62. Natures Countercurrent Heat Exchanger

Another example of a nature inspired innovative design is the concept vehicle Mercedes-Benz bionic car. Engineers, designers and biologists at Mercedes-Benz worked hand in hand to develop the innovative concept shown in figure 63.



Fig. 63. Concept vehicle Mercedes-Benz

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The design was based on a sea dweller from tropical latitudes: Ostracion Cubicus which is more commonly known as the boxfish. The rectangular anatomy of the boxfish is practically identical to the cross-section of a car body. The fish is an excellent swimmer having extremely good aerodynamic characteristics and can move with a seemingly minimal amount of effort. Wind tunnel tests of a 1/4 scale model of the Mercedes-Benz bionic car have yielded surprisingly very low drag. The boxfish is also a marvelous natural structural concept and is able to withstand high pressures as a result of its outer skin structural design consisting of tiny interlinked hexagonal bone plates which provide maximum strength with minimal weight and effectively protect the animal from injury. It can survive unscathed following collisions with corals or other sea dwellers. In consultation with bionics experts, the automotive researchers developed a computer-assisted process for transferring the growth principle used by nature to automobile engineering. It is based on the SKO method (Soft Kill Option). Computer simulations were used to configure body and suspension components in such a way that the material in areas subject to lower loads was reduced, and in certain instances, even eliminated ("killed") completely, while highly stressed areas were specifically reinforced. This bionic SKO process enabled an optimal component geometry to be identified which meets the balanced requirements of lightweight construction, safety and durability. The boxfish is a prime example of the ingenious inventions developed by nature over millions of years of evolution. The basic principle of the evolutionary developments is that nothing is superfluous and each part has a purpose and often several at once.

Large African termite mounds as shown in figure 60 provide the incredible ability of termites to maintain virtually constant temperature and humidity in their homes despite an outside temperature variation from 37 °F at night to 108 °F during the day. The column of hot air rising in the above ground mounds helps drive air circulation currents inside the subterranean network. The structure of these mounds can be quite complex. The temperature control is essential for those species that cultivate fungal gardens and even for those that don't, much effort and energy is spent maintaining the brood within a narrow temperature range, often only plus or minus one degree over a day. Termites build their massive towers, some of which rise to 25 feet, with a natural cement made from a mixture of saliva, sand and excrement to make a material as hard as rock and can only be demolished by dynamite⁵⁴.

Project TERMES (Termite Emulation of Regulatory Mound Environments by Simulation) scanned a termite mound, created 3-D images of the mound structure and provided the first ever glimpse of construction concepts that may likely change the way we build our own buildings. The Eastgate Centre shown in figure 64 is a mid-rise office complex in Harare, Zimbabwe, which was designed to emulate the temperature control concepts of the termite mounds. The East gate Center stays cool without air conditioning and uses only 10% of the energy of a conventional building of the same size.



Fig. 64. Natures Passive Air Conditioning Concept

16. "NEO-BIONICS" AS A SOURCE FOR DESIGN INSPIRATION

Neo-Bionics is an innovation approach that utilizes biological evolutionary or optimization processes found in nature as the computational strategy for a computer aided design optimization with engineering constraints. Neo-bionics can be defined as "Computational Inspiration"

Some of the biologically inspired optimization techniques include

- Genetic Algorithms (GA)
- Particle swarm optimization (PSO)
- Evolutionary structural optimization (ESO)
- Bidirectional evolutionary structural optimization (BESO)
- Soft Kill Option, (SKO)

A genetic algorithm (GA) is a search technique used in computing to find exact or approximate solutions to optimization and search problems. Genetic algorithms are categorized as global search methods that use techniques inspired by evolutionary biology such as inheritance, mutation, selection, and crossover (also called recombination). Genetic algorithms have been utilized in such varied fields as bioinformatics, phylogenetics, computational science, engineering, economics, chemistry, manufacturing, mathematics, physics and other fields.

Figure 65 illustrates how unexpected fundamental concepts can arise from robust configuration optimization using genetic algorithms, GA. In this example ^{45, 46, 47} an evolutionary optimization algorithm was used to find the wing geometry that produced minimum total drag, yet fit inside a geometric constraint box of fixed height and span.



Figure 65: Neo-bionic Innovative Configuration Development

The wing was described as a collection of variable length linearly tapered and twisted elements, whose aerodynamic characteristics were computed using a vortex lattice analysis. A random population of initially simple designs is shown at the top left side of figure 65. The optimizer quickly discovered that span reduces drag, and after only 5-6 generations (with population size 500), and found the minimum induced drag for a roughly planar wing. As the span limiting constraint become active, the optimizer "discovered" winglets, adding vertical elements at the wing tips to further reduce vortex drag. Finally, after about 100 generations, the system found an advantage to adding horizontal tip extensions to the winglets, forming a "C" shape at the tip that lies within the upper geometric box constraint.

This "C" wing design concept was investigated further and found to exhibit useful structural and control features in addition to the reduced vortex drag at fixed span. The concept was subsequently patented and is being studied for application to new aircraft concepts at Boeing, NASA and elsewhere.

Another example of a neo-bionic design study³³ is shown in figure 66. In this example a genetic algorithm was used in conjunction with a wind tunnel test program to determine the optimum orientation of a set of five wing tip segments. During the optimization, the GA would specify the orientation of each of the segments that were then subsequently tested. After about 27 generations an improvement of approximately 11% in lift to drag ratio, L/D, was achieved



Fig. 66. Evolution of Slotted Wing Tips in the Wind Tunnel

Particle swarm optimization (PSO) is a population based stochastic optimization technique that was inspired by social behavior of bird flocking or fish schooling. PSO shares many similarities with evolutionary computation techniques such as Genetic Algorithms (GA). The system is initialized with a population of random solutions and searches for optima by updating generations. However, unlike GA, PSO has no evolution operators such as crossover and mutation. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles. Compared to GA, the advantages of PSO are that PSO is easy to implement and there are few parameters to adjust. PSO has been successfully applied in many areas: function optimization, artificial neural network training, fuzzy system control, and other areas where GA can be applied.

The evolutionary structural optimization (ESO) method⁴⁸ is based on the simple concept of gradually removing underutilized material from a structure so that the resulting shape evolves towards an optimum. The ESO method proves to be capable of solving size, shape and topology structural optimization for static, dynamic, stability and heat transfer problems or combinations of these. The traditional ESO method removes material from a structure based on von Mises stress or strain energy of each element. For certain construction materials, such as concrete and fabric, they are only suitable for sustaining compressive or tensile stress. The ESO method has been extended to the design of tension-only or compression-only structures. The validity of the ESO method depends, to a large extent, on the assumptions that the structural modification (evolution) at each step is small and the mesh for the finite element analysis is dense. If too much material is removed in one step, the ESO method is unable to restore the elements which might have been prematurely deleted at earlier iterations. Consequently, In order to make the ESO method more robust, a bi-directional ESO (BESO) method has been developed which includes both the adding and removing of material during the optimization process.

Figure 67 shows the use of the BESO algorithm are given in to design an optimized bench design. The top layer of the bench is defined as a non-design domain. The initial design has four support legs. By adding and removing material simultaneously, BESO finds the optimal solution shown the figure. The figure also shows the initial four leg support system and three additional geometries leading to the optimum stool design.



Used with permission, Dr. Mike Xie, George Washington University Center for Biomimetrics and Bioinspired Engineering.

Fig. 67. BESO Optimized Stool Design

The SKO, soft Kill Option is a relatively new method for structure optimization that was developed to transfer the growth principle used by nature to engineering structural design. In the book Design in Nature: Learning from Trees⁴⁹, Prof. Mattheck introduced what he called the Principle of Constant Stresses derived from analogies observed in the growth of trees⁵⁰. He found that the trees adjust their growth in a fashion such that the stresses on the surface are equally distributed. Stress peaks that occur will be reduced by a stress proportional growth in that area. He also observed that in nature, all unnecessary material is avoided and that material decays where it is no longer needed.

Based on these bionic observations, he introduced what he called the Soft Kill Option (SKO). By varying the young's modulus in a structure, he rewards the elements that carry more of the load by increasing the young's modulus and simulating material growth in the area. He punishes the elements at lower stress states by decreasing their respective young's modulus. By this, the 'lazy' elements increasingly withdraw themselves from carrying the load and once they do not contribute significantly, he purges them from the set of elements. This process enables an optimal component geometry to be identified that meets the requirements of lightweight construction.

The SKO method has become an integral part of Daimler Chrysler's vehicle development engineering processes⁵¹. In the case of a car door, for example, this honeycomb-design method increases stiffness by up to 40 percent, while the weight is reduced by around 30 percent, based on calculations using the SKO method. If the entire body shell structure is configured according to the SKO method, its weight is reduced by around 30 percent – while retaining its exemplary stability, crash safety and handling dynamics. The SKO method has since been used for producing components such as the engine support arms that are fitted on some rural-service buses. The bone-plate skeleton of the previously discussed boxfish demonstrates how nature is able to achieve an optimal structural design. The hexagonal structural scales of the boxfish obey the principle of maximum strength for the least weight.

It should be noted that the aforementioned structural optimization methods have no proof that they will achieve an optimal design but experience has shown that the application of these straightforward methods will result in lighter and durable structures. The weight saving efficient structural design concepts obtainable by these evolution based design methodologies clearly shows that bionics can make contributions to greater fuel economy and operational economics for both the automotive and aerospace industries through the development of lightweight efficient structural designs.

17. "PSEUDO-MIMICRY" AS A SOURCE FOR DESIGN INSPIRATION

Pseudo-Mimicry relates to technology developments or innovative concepts that are not directly inspired by nature, having similar but unrelated functions. Sometimes we do not copy nature, but we re-discover our own inventions in a similar but unrelated concept of nature. We will extend this definition of pseudo-mimicry to include designs that may have similar functions but were not directly influenced by an awareness of nature's similar design. Since natures designs have been refined over periods of millions of years, finding a design or concept in nature that is similar to one of our creations tends to suggest that we are probably on the right track.

The Proteus shown in figure 68 is a twin turbofan high altitude multi mission aircraft powered by Williams International FJ44-2E engines. It is designed to carry payloads in the 2000-pound class to altitudes above 60,000 feet and remain on station up to 14 hours. Heavier payloads can be carried for shorter missions. It is intended for piloted as well as for UAV

missions. Missions for Proteus include telecommunications, reconnaissance, atmospheric research, commercial imaging, and space launch. The Proteus is designed with long wings and a low wing loading needed for efficient high altitude loiter. It excels in stability and low noise. It is capable of dynamic maneuvers, needed to operate in adverse conditions. The crisp, short takeoff and landing uses the unique "three-mains" landing gear design intended to increase crosswind and wet runway capability without the use of spoilers. The shape of the Proteus¹ is very similar but certainly unrelated to the Microraptor gui shown in the figure. The chicken-sized Microraptor, which lived in the early Cretaceous period some 140 million years ago, had long flight feathers on its forelimbs and feet, and relied its a biplane-like wing configuration to swoop from tree to tree.



Figure 68: Tandem Wing Fliers

The cross section of a birds wing in figure 69 shows a light weight structure sandwich design that nature developed using its' evolutionary version of Soft Kill Optimization. The design is very similar to that of a Warren truss as well as the structural concept used for the fuselage designs of the early aircraft. Construction of a Warren truss like structure features longerons, as well as diagonal and vertical web members. As technology progressed, aircraft designers began to enclose the truss members to streamline the airplane and improve performance. This was originally accomplished with cloth fabric, which eventually gave way to lightweight metals such as aluminum. In some cases, the outside skin can support all or a major portion of the flight loads. Most modern aircraft use a form of this stressed skin structure known as monocoque or semi-monocoque construction.



Figure 69: Structural Design Concepts

The aerodynamic concept of the leading edge slat on an airfoil or wing performs the same function as the alula that exists on the wings of some birds. Both concepts which are shown in figure 70, help to restore or retain attached flow around the leading edge and thereby increase the maximum achievable lift coefficients, CLmax. Birds as well such equipped aircraft use their respective leading edge devices to provide lower landing speeds. It has been reported that birds without alula dramatically reduce their ability for takeoff and landing⁵².



Figure 70: Alula- Natures Leading Edge Slats

Figure 71 Shows the technology development stages of a low noise serrated trailing edge nozzle design which is very similar to the soft, serrated wing trailing edge of an owl that also diffuses and reduces high frequency noise⁵³. The owl has a number of additional low noise evolutionary developments since stealth is critical to its survival.



Fig. 71. Biological and Technological Similar Noise Reduction Concepts

Wheels do not appear to play a significant role in the locomotion of biological systems. This lack of biological "wheels" has been a frequent topic of semi-serious debate among biologists. Rotating locomotion incurs mechanical disadvantages in certain environments and situations which may help to explain why multi-cellular life has not evolved wheels for

locomotion. Although wheels are more energy efficient than other means of locomotion when traveling over hard, level terrain (such as paved roads), wheels have several distinct disadvantages that stem largely from the fact that many natural environments are ill-suited to the use of wheels.

Some organisms do use rolling as a means of locomotion. However the entire organism rotates itself. A species of caterpillar known as the Mother-Of-Pearl Moth, curls into a ring and rolls away when threatened. The salamander Hydromantes platycephalus also curls up and rolls downhill to escape danger. The tumbleweed, Corispermum hyssopifolium uses passive rolling, powered by wind, to distribute its seeds. The dung beetle uses rolling to transport the feces on which it feeds. It is appropriate then, to say that Nature did invent the wheel, it just forgot the axel.

A species of mantis shrimp, the stomatopod crustacean Nannosquilla decemspinosa rolls back to the water by means of backward somersaults and consecutive rolling by forming a wheel with its entire body, if a wave washes it onto the sand beach as shown in figure 72. In a sense, it can be said that nature also invented the continuous track used on many of our specialized vehicles.



Fig. 72. Nature Invented the Continuous

18. "CYBERNETICS" AS A SOURCE FOR DESIGN INSPIRATION

Cybernetics will be defined as the science of reverse engineering of nature using analytical tools and methodologies to examine nature in great detail to gain an understanding of nature's designs, functions and operational procedures and thereby enable bionic or biomimicry innovations. John. McMasters stated that "Engineers, working closely with those from a range of scientific disciplines (e.g. zoology, botany, paleontology, neuro-physiology, geology, and particularly ecology), have much to contribute to increasing our understanding of flight in nature and engineering in general."

Figure 73 illustrates an integrated approach to assimilate results of independent and / or coordinated studies using the various tools of the aerodynamicist to develop the knowledge data base defining the mechanics of insect flight. The understanding formulated from the knowledge database is then applied to the development of an artificial flying insect.



Fig. 73. Integrated Approach to Reverse Engineering of Nature

We have all probably observed at various times the magnificent aerobatic displays of large flocks of birds as shown in figure 74, which appear to be ordered patterns of chaotic undirected motion, often without an apparent purpose or global objectives. Similar types of swarming motion are displayed by insects as well as by schools of fish.

A swarm of bees or a flock of birds can be assumed to consist of 'N' number of agents. These autonomous agents are in some way co-operating to achieve a global objective. This global objective can include better foraging, constructing shelter, or serving as a defense mechanism. The apparent collective intelligence of a swarm emerges from actions of the individual agents. The actions of these agents are governed by local rules of interactions of the N agents. A kind of "self organization" emerges in these systems⁵⁴. The individual (but autonomous) agent does not follow directives from a central authority or work according to some global plan. As a common example, a bird in a flock, only adjusts its movements to coordinate with the movements of its flock mates or more precisely the members that are its neighbors. It simply tries to stay close to its neighbors, but avoid collisions with them. Each bird does not take commands from any leader bird since there is no lead bird. Any bird can fly anywhere in the swarm, either in the middle or the front or the back of the swarm. Swarm behavior gives the birds some distinct advantages like protection from predators, and searching for food.



Starling Swarm Sequence. Credit: Dylan Winter, used with permission used with permission



Predator / Flock Simulation With Boids Particle System, Credit Ennio Fioramonti.

Figure 74: Bird Swarms and Group Dynamics

Craig Reynolds, a computer graphics researcher, in 1986 created a deceptively simple steering program called boids⁵⁵. The boid model has in its implementation, simple rules to explain and predict the motion of a flock of birds. Each boid observes the following rules.

- 1. Boids try to fly towards the centre of mass of neighboring boids.
- 2. Boids try to keep a small distance away from other objects (including other boids).
- 3. Boids try to match velocity with near boids.
- Flake⁴⁷ later added a Fourth rule, a boid should move laterally away from any boid that blocks its view.

This simple model as shown in the lower part of figure 74 appears to accurately predict the motion of the flock and the agents within the flock. Swarm intelligence as predicted by the boid model provides a basis which makes it possible to explore collective (or distributed) problem solving without centralized control. A team of robots that could coordinate its actions like a flock of birds could offer significant advantages over a solitary robot. Spread out over a large area, a group could function as a powerful mobile sensor net, gathering information about what's out there. If the group encountered something unexpected, it could adjust and respond quickly, even if the robots in the group weren't very sophisticated.

Figure 75 shows lifted covert feathers on a brown skua and on a crow at landing conditions. It has been hypothesized that these coverts are passively lifted to prevent the forward movement of the separated flow that develops initially near the trailing edge as a bird increases its attitude to slow down and land. Experimental studies⁵⁶ of a passively lifting "eddy flap" as shown in the figure, indicate that the effect was to prevent sudden drop in lift generation during stall. Measured pressure distributions indicate that the eddy-flaps restrict the separation eddy to aft part of aerofoil.



Fig. 75. Covert Feathers as "Eddy Flaps"

Jumping can be a very efficient mode of locomotion for small robots to overcome large obstacles and travel in natural, rough terrain. Professor Dario Floreano and his colleagues at the Laboratory of Intelligent Systems, Swiss Federal Institute of Technology have developed a novel 5cm, 7g jumping robot that can jump obstacles than 24 times its own height as shown in figure 76. It employs elastic elements in a four bar linkage leg system to allow for very powerful jumps and adjustment of jumping force, take off angle and force profile during the acceleration phase. This jumping mechanism is very similar to natures jumping mechanism of the grasshopper previously discussed and shown in figure 48. This is an example of being inspired by nature and then surpassing nature's capability as seen in the standing high jump records bar chart.



Images Courtesy, Professor Dario Floreano, Laboratory of Intelligent Systems, Swiss Federal Institute of Technology

Fig. 76. Tiny 7g Jumping Mechanism Prototype.

Dr.Robert Full of the University of California, Berkeley, Department of Integrative Biology and his colleagues have conducted a number of clever experiments to determine the performance characteristics of natures foot designs. In some of their experiments they observed grass spiders and coachroaches run across a mesh with 99% of the contact area removed. Neither insect slowed down when crossing the mesh. Upon further investigation, they determined that the foot of either a spiders or a cockroach is distributed along the whole leg as shown in the left picture in figure 77.



Courtesy of Dr. Robert Full, University of California, Berkeley, Department of Integrative Biology Fig. 77 Natures Distributed Foot.

Courtesy of Boston Dynamics, ©, 2009

Crissy Huffard, Robert Full and Farnis Barneka reported the first scientific documentation of underwater "bipedal" locomotion of any animal in the March 25 issue of the journal Science. These are shown in the middle pictures in figure 77, and include a bipedal octopus disguised as a rolling coconut and one that disguises itself as floating algae which walks on two legs and holds its other arms up in the air. The distributed foot designs make it possible to move over obstacles as though they are not even present. It has been postulated that the two-armed walking behavior allows the octopus to slowly walk away from a predator while preserving its existing camouflage.

The distributed foot concept is an integral part of the Robot Hexapod, RHex, developed by Dr. Full, in collaboration with Daniel Kodistchek of the University of Michigan, Martin Buehler at Canada's McGill University and Boston Dynamics. RHex has self-correcting reflexes — "preflexes," that act like springs and shock absorbers that help it overcome obstacles. RHex climbs over rock fields, mud, sand, vegetation, railroad tracks, up steep slopes and stairways. RHex has a sealed body, making it fully operational in wet weather, in muddy and swampy conditions, and it can swim on the surface or dive underwater.

Figure 78 shows a series of nature inspired mobility concepts developed by Boston Dynamics.

Application of Natures "Animal Mobility" Concept Application of Natures "Animal Mobility" Concept Application of Natures "Gecko Foot Concept"



Images courtesy of Boston Dynamics, ©, 2009

Fig.78. Other Nature Related Mobility Concepts

LittleDog is a quadruped robot for research on learning locomotion. Scientists at leading institutions use LittleDog to probe the fundamental relationships among motor learning, dynamic control, perception of the environment, and rough terrain locomotion. LittleDog has four legs, each powered by three electric motors. An onboard PC-level computer does sensing, actuator control and communications. LittleDog's sensors measure joint angles, motor currents, body orientation and foot/ground contact.

BigDog is a quadruped robot that walks, runs, and climbs on rough terrain and carries heavy loads. BigDog is powered by a gasoline engine that drives a hydraulic actuation system. BigDog's legs are articulated like an animal's, and have compliant elements that absorb shock and recycle energy from one step to the next. BigDog is the size of a large dog or small mule, measuring 1 meter long, 0.7 meters tall and 75 kg weight. BigDog's control system manages the dynamics of its behavior to keep it balanced, steer, navigate, and regulate energetics as conditions vary. Sensors for locomotion include joint position, joint force, ground contact, ground load, a laser gyroscope, and a stereo vision system. BigDog weighs about 250 lbs and can carry a load of 340lbs.

RiSE is a small six-legged robot that climbs vertical terrain such as walls, trees and fences. RiSE's feet have claws, micro-claws or sticky material, depending on the climbing surface. RiSE changes posture to conform to the curvature of the climbing surface and a fixed tail helps RiSE balance on steep ascents. RiSE is about 0.25 m long, weighs 2 kg, and travels 0.3 m/s. Each of RiSE's six legs is powered by two electric motors. An onboard computer controls leg motion, manages communications, and services a variety of sensors. The sensors include an inertial measurement unit, joint position sensors for each leg, leg strain sensors and foot contact sensors.

Insects such as the dragonfly utilize optic flow in order to navigate in and around obstacles as shown in figure 79. The term "optic flow" refers to a visual phenomenon that you experience every day. Essentially, optic flow is the apparent visual motion that you experience as you move through the world. Suppose you are sitting in a moving car or a train, and are looking out the window. You see trees, the ground, buildings, etc., appear to move backwards. This motion is optic flow. This motion can also tell you how close you are to the different objects you see. There are clear mathematical

relationships between the magnitude of the optic flow and where the object is in relation to you. Engineer and inventor Dr. Geoffrey Barrows has developed innovative optic-flow sensors to allow both aerial and ground vehicles to travel autonomously, by using the same techniques living creatures such as flying insects do to gauge their altitude and proximity to obstacles in their path.



Used With Permission: Dr.Geoffrey Barrows, Centeye Corp.

Fig. 79. Dragonfly and Optic Flow

Nature created an incredible self assembly high speed reverse direction rotary motor with a diameter of 30 nm. Mobility of bacteria, such as Salmonella and E. coli with a body size of $1 \sim 2$ microns, is driven by rapid rotation of a helical propeller by such a tiny little motor at its base. This organelle is called the flagellum, made of a rotary motor and a thin helical filament that grows up to about 15 microns. It rotates at around 20,000 rpm, at energy consumption of only around 10^{-16} W and with energy conversion efficiency close to 100%. The motor switches its direction every few seconds to change the swimming direction of the cells for bacteria to seek better environments. Dr. Keiichi NAMBA Professor, Graduate School of Frontier Biosciences, Osaka University and his colleagues are conducting cutting edge research to reveal the mechanism of this highly efficient flagellum motor that is far beyond the capabilities of artificial motors. The left picture shows two bacteria cells with their flagella extending behind. The second picture shows the design of the flagella self assembly rotary motor. Cilia use a similar motor design except the bacterial flagellum acts as a rotary propeller in contrast to the cilium, which acts more like an oar. The design concepts of nature's rotary motors have to be well understood and learned for future nanotechnology applications



Fig. 80. Nature's Rotary Engine

19. "NON-BIONIC" SOURCES FOR DESIGN INSPIRATION

Non-bionic innovative technology developments or innovative involve concepts having no apparent similar parallel in nature. The source of the inspiration will primarily come from the use of our "Tools" and our perceived understanding. Because of the background of the author, the examples in this section will be primarily aerodynamically related. However the basic concepts, strategies and concepts should apply to all technical and scientific disciplines

One of the great joys of my career was to meet and become friends with the famous US Aerodynamicist Dr. Robert T. Jones. He possessed, among many other things, the remarkable ability to share his wisdom, blended with a touch of humor.

One time when discussing linear theory and CFD, he said with a twinkle in his eyes: "*Linear theory is long on ideas but short on arithmetic, CFD is long on arithmetic but short on ideas.*" Although, linear theory can provide some unique insights and ideas, it does require understanding to correctly apply the theory because of its numerical and physical limitations. Linear theory can provide innovative ideas by inductive reasoning derived directly from the basic equations.

Similarly, the non-linear CFD methods also require a basic understanding of the inherent limitations of the methodology. However CFD can provide answers, designs and visibility for flow solutions and flow conditions far beyond the applicability limits of linear theory. CFD as well as EFD (experimental fluid dynamics) provides innovative ideas by deductive reasoning based on the interpretations, understanding and ideas that we deduce from our accumulated sets of data

By using both CFD and linear theory and exploiting the benefits of each, we can have the "ideas" and the "arithmetic" plus the added bonus of increased synergistic understanding and design capability.

Examples of some of the innovations that have been conceived using linear theory include:

- Elliptic Load Distribution for minimum induced drag
- Wing Tip Fins
- Joukowski Airfoils
- Supersonic Area Rule Body Contouring
- Sears-Haack Minimum Wave Drag Body
- Von Karmen Mininimum Wave Drag Nose
- Supersonic Favorable Interference Concepts
- Low Sonic Boom Concepts

The concept of the near sonic area rule shown in figure 81 as an example of arriving at a similar aerodynamic concept or discovery by various individuals who followed independent paths to discovery while using predominately different aerodynamic tools⁵⁷.



Fig. 81. Various Paths Leading to the Development of the NACA Area Rule

The area rule was first discovered by a team including Heinrich Hertel and Otto Frenzl working in a transonic wind tunnel, (EFD) at Junkers in Germany between 1943 and 1945; it is defined in a patent filed in 1944. The design concept was applied to a variety of German World War II aircraft.

Dr. Wallace Hayes independently developed the supersonic area rule in a series of linear theory publications beginning in 1947 with his PH.D thesis at the California Institute of technology. The sonic area rule corresponds to application of the linear theory supersonic area rule at Mach 1.0.

Richard Whitcomb was testing wing-body combinations in 1952, in the new NACA eight–foot high speed slotted-throat wind tunnel that could operate at Mach numbers up to Mach 0.95. He was surprised by the increase in drag due to shock wave formation. Whitcomb attended a talk by Adolf Busemann, a world-famous German aerodynamicist at NACA Langley. Busemann talked about the difference in the behavior of airflow at speeds approaching supersonic speeds, where it no longer behaved as an incompressible fluid. He explained that the airflow streamlines no longer contracted with the air flowing smoothly around an aircraft. At high speeds it simply didn't have time to "get out of the way". Instead the flow streamlines behaved as constant area pipes of flow bending around a configuration. Several days later Whitcomb had a "Eureka" moment, (UFD). When he realized the wave drag was caused by the entire cross-sectional area of the wing body configuration. Consequently he concluded that the flow at near sonic speeds depended on the total cross-sectional area of the configuration. This became known as the "NACA area rule". The pictures on the lower portion of figure 81 show results of the first full scale of the NACA area rule to the F-102A.

Figure 82 illustrates another approach to developing innovative concepts by utilizing a combination of simplified fluid dynamics, SFD, together with understanding UFD. Polhamus developed a very simple but elegant method to predict the development of the leading edge vortex on thin sharp leading edges⁵⁸. This method is called the suction analogy. The Polhamus suction analogy was used to develop the concept of leading edge vortex flaps to produce enhanced vortex lift.

Kulfan developed the residual suction analogy, RSA⁵⁹ that accounts for the effects of round leading edge geometries on the progressive inboard movement of the leading edge vortex with increasing angle of attack. The RSA method was used to develop a leading edge design concept for passive suppression of the leading edge vortex that resulted in substantial improvement in the lift / drag ratio at subsonic / transonic cruise conditions for the Boeing HSCT configuration

In both instances based on perceived understanding of the formation of leading edge vortices, simplified flow analogies and simple mathematical relations were developed to predict the effects on geometry on the formation and development of the leading edge vortices and the effects of the vortices on lift and drag, and the.



Fig. 82. Use of SFD Plus UFD to Develop Vortex Control Concepts

Figure 83 shows two classes of concepts that are not found in nature. The innovation for the variable sweep wing configuration was developed from LFD analyses as a very low supersonic drag configuration with the wing yawed and very good subsonic lift and drag characteristics when the wing is unyawed. The hypersonic X43 concept was conceived using CFD plus UFD.

LFD + UFD Inspired

CFD + UFD Inspired



Figure 83: Examples of Aircraft Concepts Having No Parallel Bionic

The laminar flow control technology shown in figure 84 has it roots founded in laminar flow linear stability analyses plus conceiving th active suction concept based on CFD followed by extensive EFD (wind tunnel) and RFD (flight test) experiments.





Fig. 84. Aircraft Laminar Flow Control, LFC, Technologies

20. IDEAS ARE EVERY WHERE

Ideas for innovation are everywhere as shown in figure 85 for some of the biologically inspired innovations that we have previously discussed.



Fig. 85. Ideas Are Every Where - What have we seem

What do you see in Fig. 86? Do you see a gecko' foot or do you see the potential for a super removable adhesive, a climbing robot, or a potential tall building fire rescue device? Do you see an abalone shell or a strong impact ceramic type material? Do you see a whale flipper or do you see an advanced wind turbine blade? Do you see a pine cones or smart clothing that adapts to changing temperatures? Do you see giant termite mounds or a passive cooling concept for large buildings such as the Eastgate Centre in Harare, Zimbabwe? Do you see a swamp or do you see the potential for a source for biofuel? Do you see a bat or do you see some of the many echolaction related technologies shown in the figure? Do you see a cat's shinning eyes that is due to tapetum lucidum which is a layer of tissue in the eye of many vertebrate animals, that lies immediately behind or sometimes within the retina and reflects visible light back through the retina? Or do you see such things as raised pavement marker and the other "retroflector" items shown in the figure.



Life is a journey full of many choices, obstacles and rewards. Our life and our career can each be filled with exciting discovers and blessed with wonderful achievements. As shown in the parting thoughts of figure 87, it all depends upon us, on the choices we make, what we search for, what we observe, what we learn and the actions that we take.



Fig. 87. Parting Thoughts

As shown if figure 87, inspiration times validation times utilization equals innovation, equals you. Be excited: There are many more problems to solve, concepts to create and flying vehicles to develop.

21. APPENDIX: GUIDELINES FOR AIRCRAFT DESIGN AND CAREER GROWTH

We have explored in the previous sections, various paths for biologically based innovations. In any design process we would be wise to reflect upon and to follow Dr. John Mc Masters Basic "Laws" of Airplane Design that include²¹:

- "A scientist discovers that which exists. An engineer (designer) creates that which never was." [Th. Von Kármán]
- Innovation for mere innovation's sake can be a great waste of time (and money)
- You never get something for nothing someone, somewhere always pays for lunch
- While the laws of economics are somewhat malleable, the laws of physics are not
- "If it looks good, it will fly good" is a myth that is sometime true
- Simplicity is the essence of true elegance it can also save weight and/or cost
- If you can't build it, you can't sell or use it
- They who control the purse strings control the policy
- Avoid exercises in futility, learn how to close a business case
- Absolute intellectual and professional integrity is mandatory (be willing to give up a failed idea or concept)
- Develop the Attributes of a Good Designer
 - Visionary
 - Creative, imaginative
 - Objective, critical
 - Stubbornly tenacious
 - Flexible
 - Cooperative
 - Independent
 - Nympholepsy (yearning for the unachievable)
 - Pragmatic
- Further lessons that Dr. McMasters has provided in his many writings include;
- Seek inspiration in your scientific art, your career and your life
- Observe nature we have learned much and there is much more to learn
- Maintain a life long thirst for knowledge
- Focus on Understanding
 - How organism works
 - What its devices do
 - Limitations
- Build from fundamentals
- Think out of the box
- Look beyond your technical discipline, Think and act as a vital part of a system of systems
- "Engineering is about applying knowledge (in a system of system sense) from a broad range of disciplines to create products, services and processes, that meet societal needs and enhance the quality of Life"

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