Paleoaerodynamic Explorations - Part 2: Options for Future Technology Innovations

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"Paleoaerodynamics can be defined as a rich field, imbued with a long and interesting past and an even more intriguing and hopeful future". This presentation, part 2 of a two part presentation, will focus on the intriguing and hopeful future. Part 1 focused on the long and interesting past. We will discuss biological options for design innovations. The focus will not be on a single technical discipline, but rather on all systems and technical disciplines involved in the complete airplane infrastructure and perhaps most importantly on tools, concepts and processes for technical innovation. We will look at various biologically related options for inspiration of technology innovations including:

- **Bionics**
- **Biomimicry**
- **Neo-bionics**
- **Pseudo-mimicry**
- **Cybernetics**
- **Non-bionics**

Size has a significant effect on nature's designs and performance characteristics. We will therefore use dimensional analysis, allometric scaling and similarity concepts to gain some insight into nature's designs.

I. INTRODUCTION

THIS is part two of a two part presentation related to what we called paleoaerodynamics which was defined as a rich field imbued with a long and interesting past and an even more intriguing and hopeful future. Part 1 focused on the long and interesting past. In this presentation various biological options for design innovations will be discussed. The focus will not be on a single technical discipline, but rather on all systems and technical disciplines involved in the complete airplane infrastructure and perhaps most importantly on tools, concepts and processes for technical innovation. Various biologically related options for inspiration of technology innovations will be discussed in detail including:

- Bionics
- Biomimicry
- Neo-bionics
- Pseudo-mimicry
- Cybernetics
- Non-bionics

First, why it is good to seek inspiration from nature will be discusses. Size has a significant effect on nature's designs and performance characteristics. Dimensional analysis, allometric scaling and similarity concepts to gain some insight into nature's designs will be presented. A number of examples that have been drawn from a number of cutting research activities from around the world will be used to illustrate the aforementioned biologically related options for technical inspiration. The presentation will then with some thoughts about the key elements of inspiration.

II. WHY SEEK INSPIRATION FROM NATURE?

All 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

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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 1.

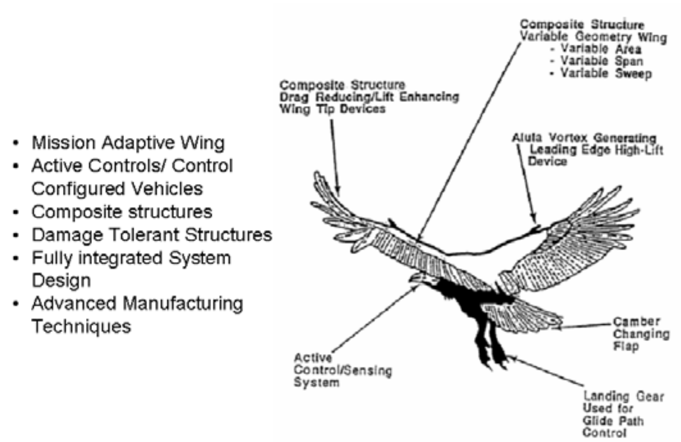


Fig. 1. Important Aeronautical Technology Incorporated In Birds

There are numerous other reasons why it is wise to seek inspiration from nature such as:

- Nature has conducted myriads of experiments over hundreds of millions of years
- Nature provides the ultimate potential reward for design improvements – the possibility of continued existence
- Natures abides by the same laws of physics, chemistry and molecular interactions
- Same source of basic materials and similar operating conditions
- There remains millions of natures inventions we have yet to discover

"*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 plant* [2]."

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.

III. SIMILARITY ANALYSES AND ALLOMETRIC SCALING STUDIES OF NATURE

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 2 contains the dimensions of various physical quantities in the Mass–Length–Time system, MLT. The physical quantities are also shown in a physiological system[3, 4] 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: geometric similarity, mechanical or dynamic similarity, kinematic or biological similarity; or 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 2.

Quantity	Dimensions		Physiological Mass Based
	Physical	Physiological	
Length	L	L	$M^{1/3}$
Mass	M	L^3	M
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	L^3	L^3	M
Velocity	Lt^{-1}	L^0	M^0
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	M
Energy	L^2Mt^{-2}	L^3	M
Power	L^2Mt^{-3}	L^2	$M^{2/3}$

Reference for discussion J.C. Georgian, The Temperature Scale, Nature, 201-595, 1964

- 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?

Fig. 2. 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 2, the relative heat loss to heat generation ratio is therefore proportional to $(\text{Mass})^{-1/3}$. 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 question by 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 3 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 height[5].

$$\text{Impulse} = M * DV \Rightarrow \Delta V \approx M^0 \quad (1)$$

The bar chart shown in figure 3 shows that the froghopper, locust and man can each achieve a maximum standing high jump of about the same 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 than the others since it jumps while lying on its back.

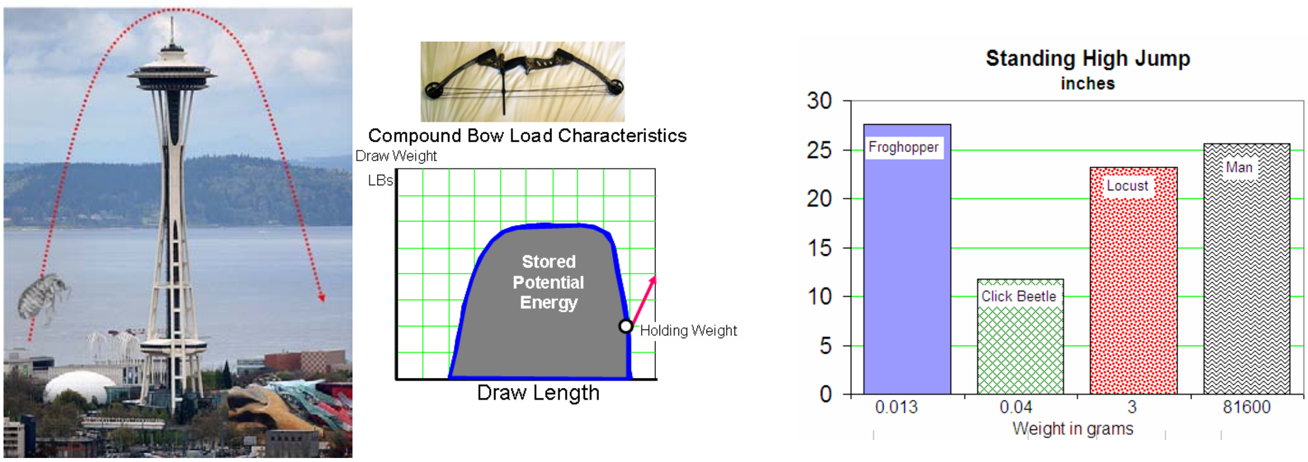


Fig. 3. If a Flea Were as Big as a Man ----------

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.

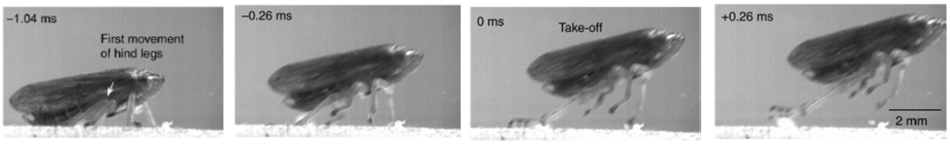
The jumping impulse is actually achieved by a finite acceleration, "ΔA" acting for a finite time "ΔT".

$$\text{Impulse} = \Delta A \cdot \Delta T$$

As shown in the table, acceleration varies with $M^{-1/3}$ and the time varies with $M^{1/3}$.

The required jumping acceleration is shown in figure 4 as a function of the mass of the jumper. The jumping acceleration for a man is about 1.75 g whereas for a flea size creature, the required jumping acceleration is about 300g to 500g. 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.

Froghopper Jumping



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

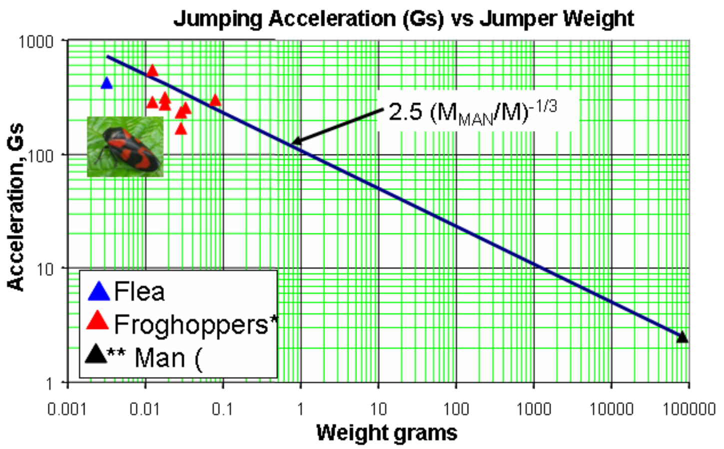


Fig. 4. Jumping Accelerations of Fleas, Froghoppers and Man

Animal	Wt, lbs	
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

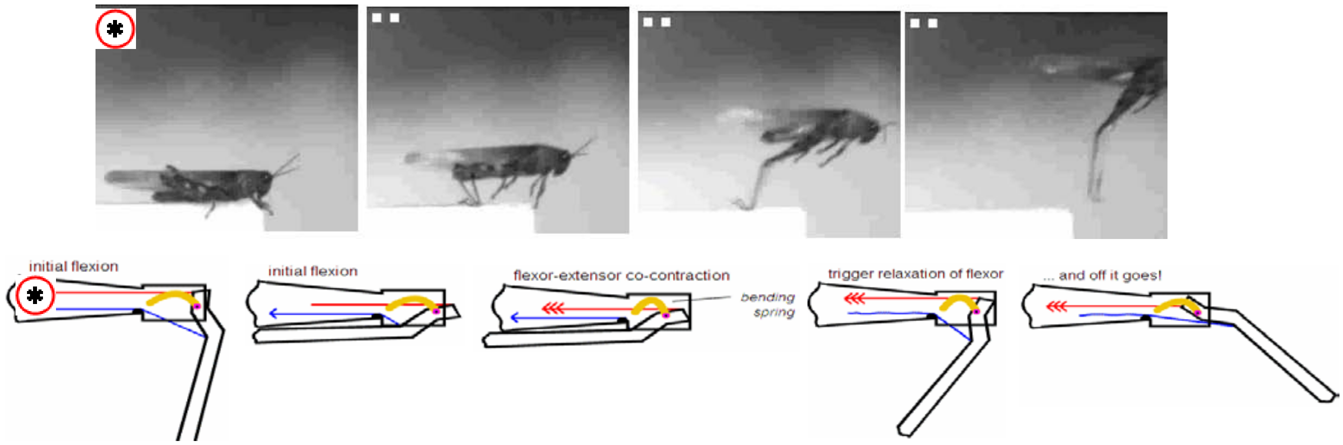
Fig. 5.Weight Range of Various Mammals

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 energy[6].

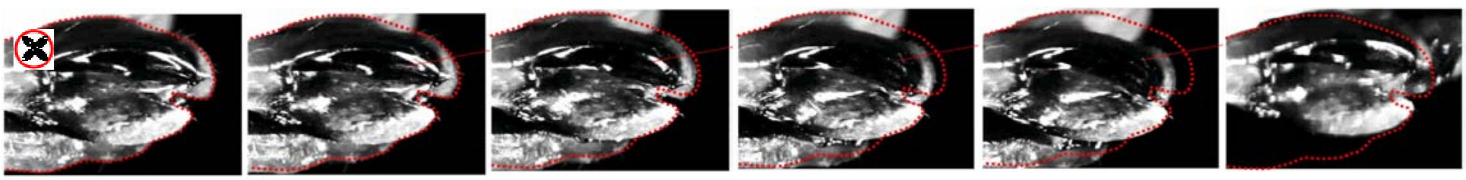
This is very similar to the mechanism of a zero holding weight compound bow. The archer converts chemical energy in his muscles to potential energy elastic energy in the limbs of the bow, by drawing the bow string back. The stored potential energy is indicated by the gray area in the figure. By proper 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 froghopper[30] is shown in figure 4. 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 Cambridge[6].

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 5.

Professor Heitler and his colleagues at the School of Biology at the University of St. Andrews, Scotland have conducted extensive studies[7] 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 6 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. 6. Jumping Mechanism of a Grasshopper

Figure 7 shows some comparative measurements for a number of birds and insects[5]. 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	$\approx M$	$\approx M^{1/3}$	$\approx M^{-1/3}$	M^0	M	M^0

Fig. 7. Size Effects on Natures Flyers

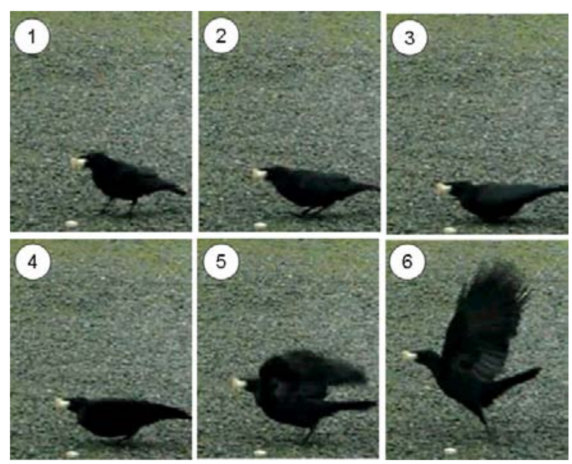


Fig. 8. Jumping Liftoff of a Crow

The wing span is seen 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 humming bird 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 8, show a crow first crouching and then leaping up to get airborne as it starts to flap its wings. A bird can also lift off by simply facing into a strong wind and then start to flap its wings.

J.B. Pettigrew in his book[8], ANIMAL LOCOMOTION or WALKING, SWIMMING, AND FLYING, WITH A DISSERTATION ON AERONAUTICS, which was published in1873, stated: *"All birds which do not, like the swallow and humming-birds, drop from a height, raise themselves at first by a vigorous leap, in which they incline their bodies in an upward direction, the height thus attained enabling them to extend and depress their wings without injury to the feathers. By a few sweeping strokes delivered downwards and forwards, in which the wings are made nearly to meet above and below the body, they lever themselves upwards and forwards, and in a surprisingly short time acquire that degree of momentum which greatly assists them in their future career."*

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 9 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 than two orders of cruise speed variation (meters/sec.).

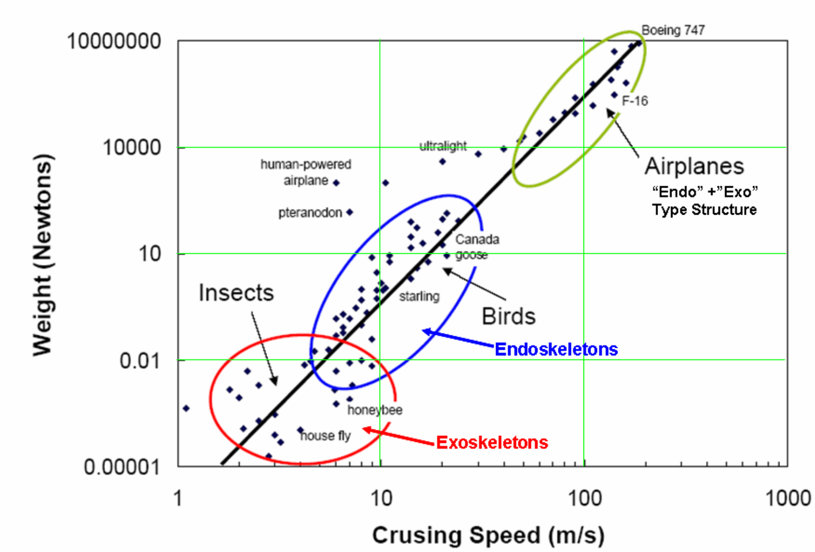


Fig. 9. Cruise Speeds for Insects, Birds and Airplanes

It is interesting to convert the data of figure 9 into relative velocity which we will define as speed per physical logical length. Relative Velocity = Velocity / Physiological length = Velocity / $(\text{Weight})^{1/3} \approx (\text{Weight})^{-1/6}$. The results are shown in figure 10. On a relative basis, a small insect cruise speed is approximately 100 times faster than that of a modern commercial aircraft.

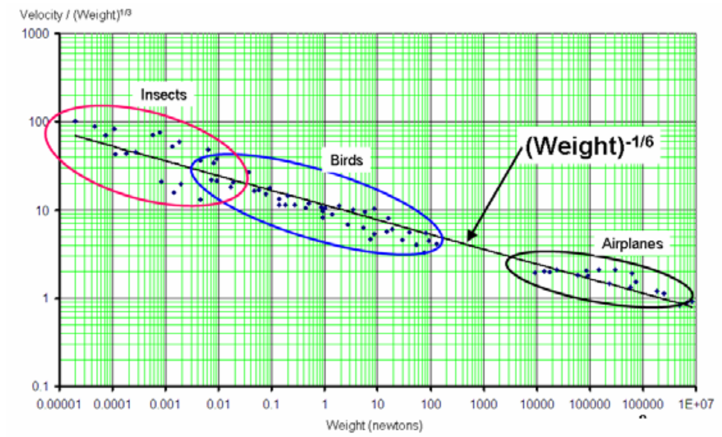


Fig. 10: Relative Velocity Versus Weight

Cruising speeds of some of nature's flyers are compared with various wind conditions in figure 11. 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. 11. 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 12, 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 13 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 bustard[9].

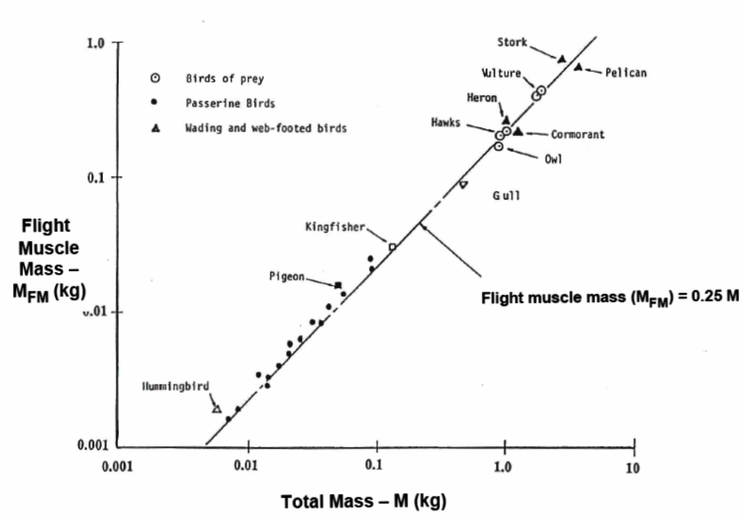


Fig. 12. Flight Muscle (Power Available) vs Total Mass in Birds.

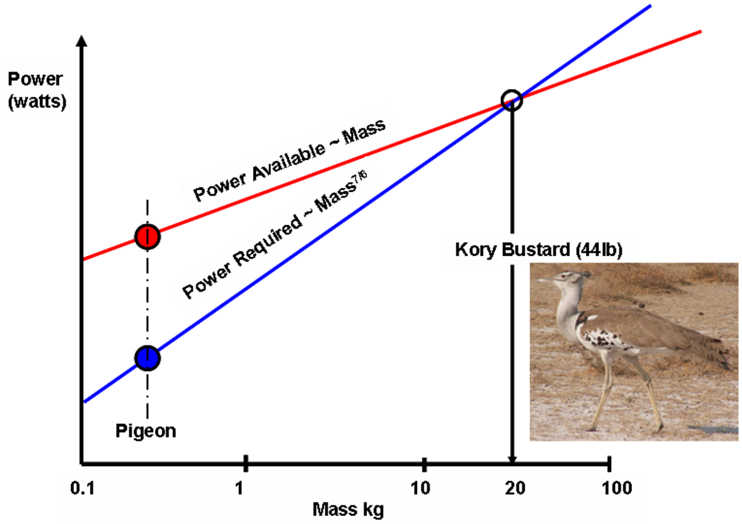


Fig. 13. Power Requirements for Steady, Level Flight

IV. "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-Smith[10] 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 is considered to be the biological inspiration for the flying wing as shown in figure 14.

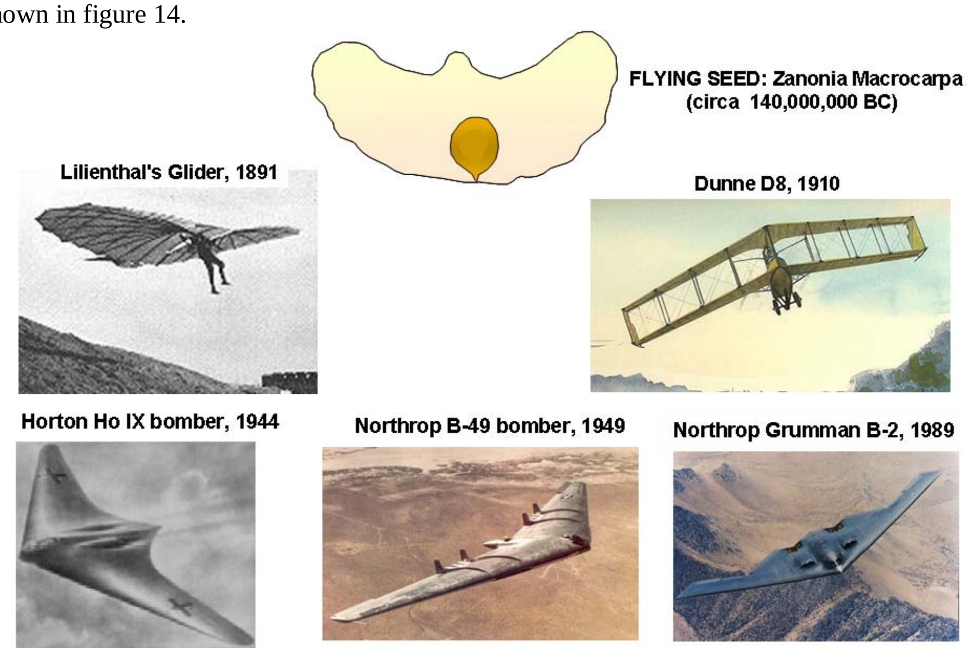


Figure 14: Zanonia Macrocarpa and the Evolution of the Flying Wing

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 15. This induced drag reducing innovative concept, was derived from the spread primary feathers of a large soaring type bird as shown in the figure.

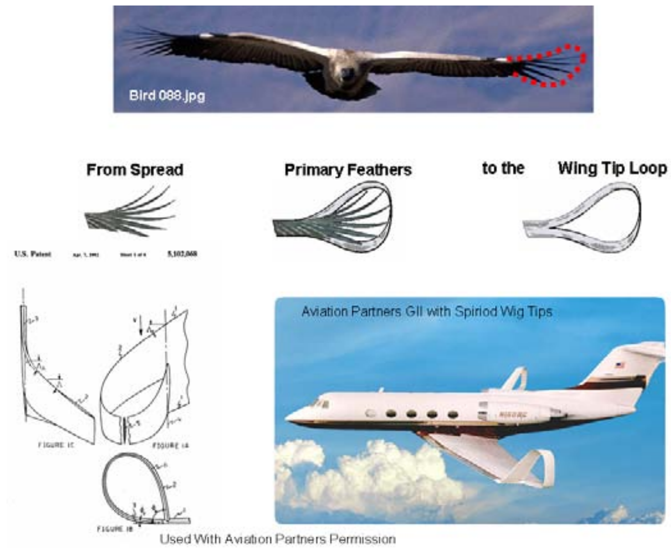
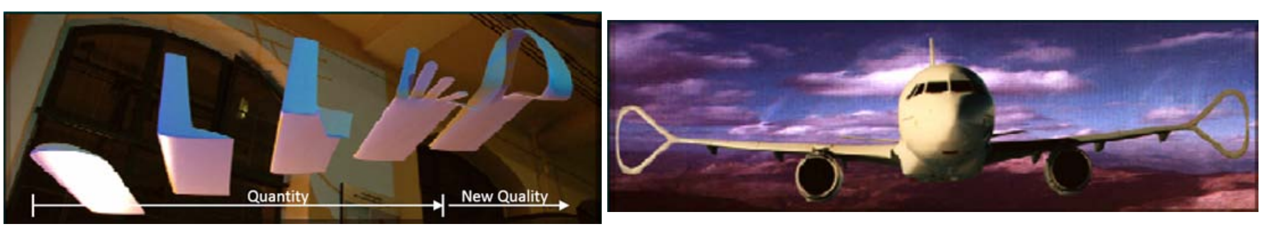


Fig. 15. Spiroid Wing Tip Bionic Innovation

Bionics studies on the aerodynamics of bird flight which were carried out by Dr. Bannasch of EvoLogics R&D Lab Bionics[11], 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 16.



Used with permission: Dr. Rydolf Bannasch, EvoLogics GmbH

Fig. 16. Independent Bionic Wing Tip Invention

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 17.Compared to regular propellers the bionic propeller sheds a continuous sheet of vorticity without core vorticies. Test results shown in figure 17 indicated that the bionic propeller increased power output from 20% to 50% and reduced the noise emission by 50%.

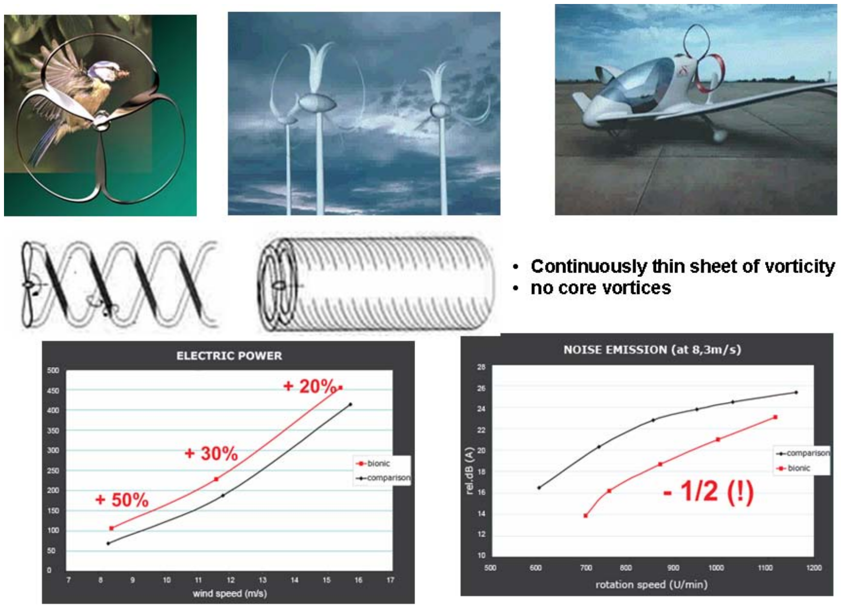


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Fig. 17. Bionic Loop Propeller

Other bio-inspired investigations [12-18] have focused on efficient fuel saving flight techniques such as formation flying (figure 18). 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.

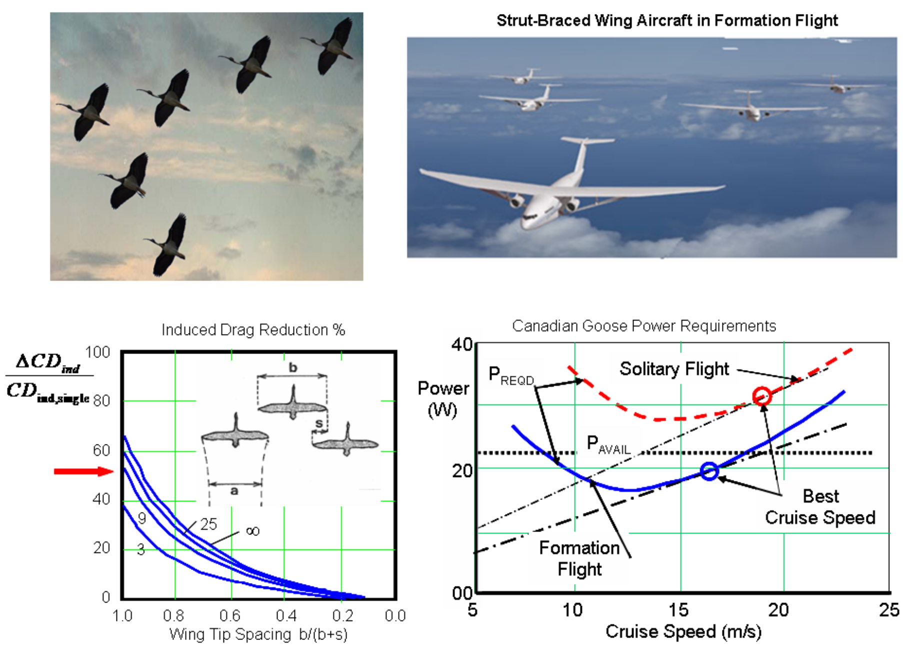

Fig. 18. Formation Flight

V. "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 problems[19]. Phil Gates[20] 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"s*[21].

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 19 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.

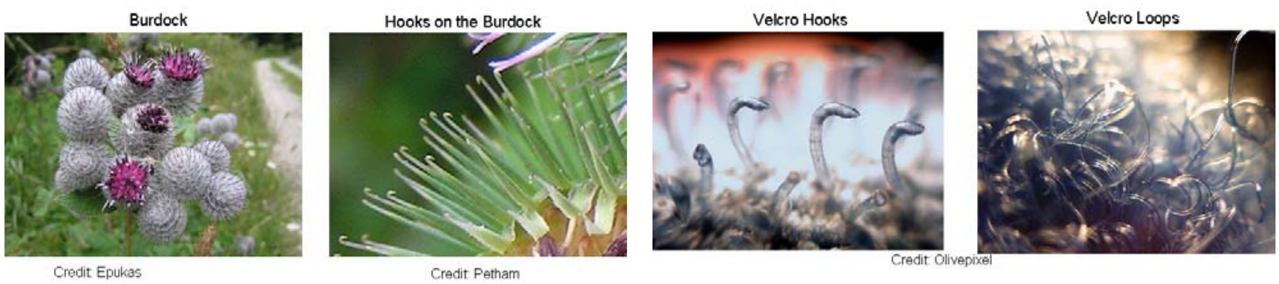

Fig. 19. The Burdock Plant and Velcro

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.
- 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 20, 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.

Figure 20: The Lotus Leaf Superhydrophobic Surface

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 system[22]. 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 21. 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.

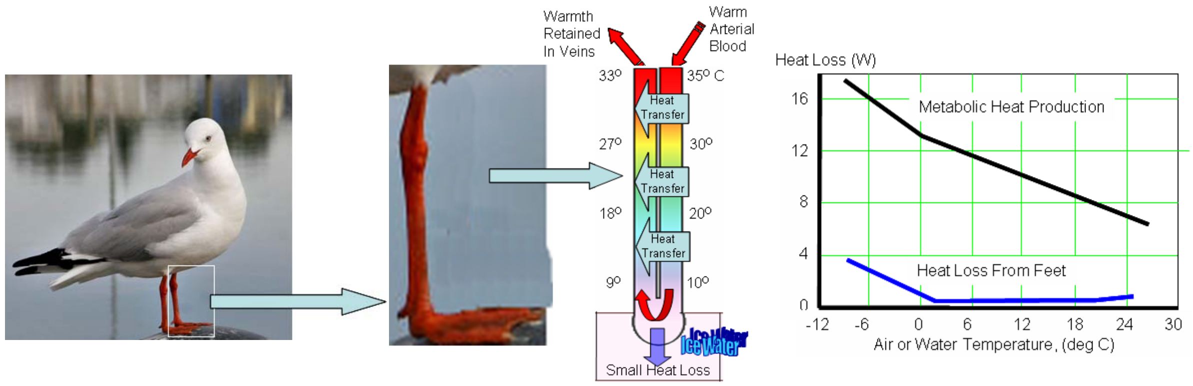

Fig. 21. Natures Countercurrent Heat Exchanger

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 22.

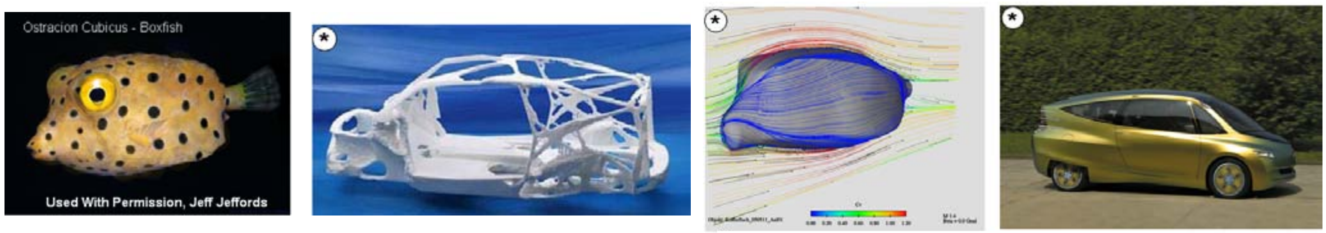

Fig. 22. Concept vehicle Mercedes-Benz

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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 23 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 dynamite.

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.

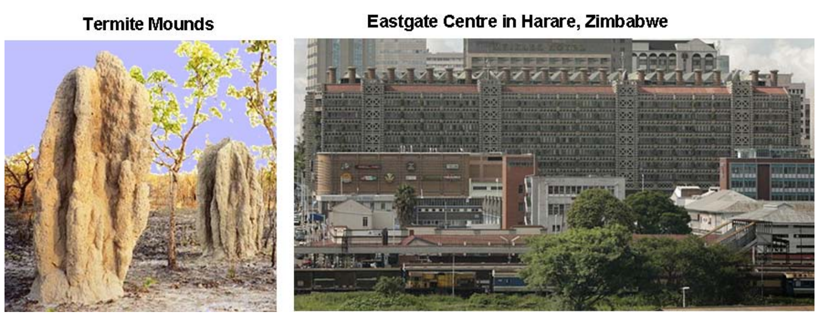


Fig. 23. Natures Passive Air Conditioning Concept

Zebras are herd animals, the stripes may help to confuse predators - a number of zebras standing or moving close together may appear as one large animal, making it more difficult for the lion to pick out any single zebra to attack. A herd of zebras scattering to avoid a predator will also represent to that predator a confused mass of vertical stripes travelling in multiple directions making it difficult for the predator to track an individual visually as it separates from its herdmates. Dazzle camouflage paint scheme similar to the stripes on a zebra was used on ships, extensively during World War I and to a lesser extent in World War II as shown in figure 24. Dazzle did not conceal the ship but made it difficult for the enemy to estimate its speed and heading. Its purpose was confusion rather than concealment. An observer would find it difficult to know exactly whether the stern or the bow is in view; and it would be equally difficult to estimate whether the observed vessel is moving towards or away from the observer's position.

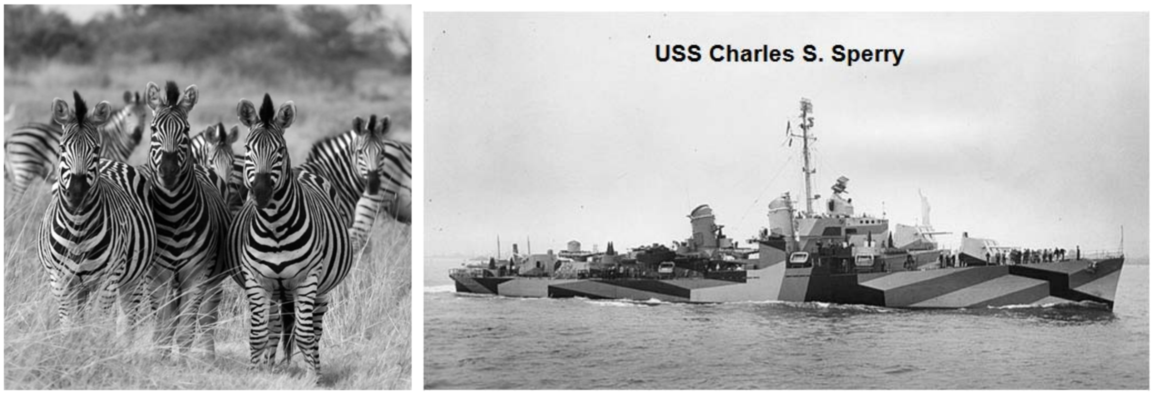


Fig. 24 Dazzle Camouflage

VI. “NEO-BIONICS” AS A SOURCE FOR DESIGN INSPIRATION

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

Some of the familiar biologically inspired optimization techniques include

- Genetic Algorithms (GA)
- Particle swarm optimization (PSO)
- Ant Colony Optimization (AC)
- Simulated Annealing (SA)
- Evolutionary structural optimization (ESO)
- Bidirectional evolutionary structural optimization (BESO)
- Soft Kill Option, (SKO)

Biologically inspired optimization techniques can be described as iterative global search techniques for a "best solution" using design of experiment methods based on nature related adaptation processes to define specific combinations of values for the design variables to evaluate in a systematic approach to "get better". Typically, each “optimization” begins with evaluations of random set of specified parameter values to evaluate, followed by the nature related "rules" to define subsequent "next case" analyses to systematically update the set of potential parameter values and progressively move towards the desired "best" solution.

The selection of the set of design parameters plus specified ranges of allowable values for each of the parameters, define the "design space" within which the selected nature related DOE process can hopefully operate to find a best solution. Because of the random nature of the initial selections of the design parameter values plus the typically independently defined parameter limits, the "design space" is most often highly irregular and seeded with many unacceptable design possibilities. Nevertheless, numerous applications of these processes have led to very effect "best solutions". The "best solution" is usually defined as the conditions for the best value of the merit functions after a specified number of solution evaluations or if subsequent solutions fail to improve the figure(s) of merit.

These techniques in general do not fit the definition of pure mathematical optimization since there exists no mathematical definition to identify an optimum solution other than the apparent convergence of subsequent merit function evaluations. In addition the various optimization techniques are not equally effective for every class of problem.

A genetic algorithm (GA) use techniques inspired by evolutionary biology such as inheritance, mutation, selection, and crossover (also called recombination) to define subsequent combinations of design parameter values to evaluate in the search for a best solution. Genetic algorithms have been utilized in such varied fields as bioinformatics, phylogenetics, computational science, engineering, economics, chemistry, manufacturing, mathematics, physics and other fields.

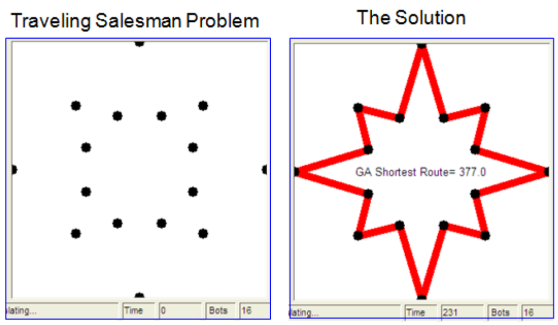
Particle swarm optimization (PSO) is a population based stochastic optimization technique that was inspired by social behavior of bird flocking or fish schooling. PSO shares many similarities with evolutionary computation techniques such as Genetic Algorithms (GA). However, unlike GA, PSO has no evolution 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 also been successfully applied in many areas: function optimization, artificial neural network training, fuzzy system control, and other areas where GA could also be applied.
Ant colony optimization is based on the foraging behaviors of ants. Simulated annealing is based on the process of the formation of crystals.

Real-world systems such as the flocking of birds, formation of crystals and the foraging behaviors of ants are examples of group behavior resulting from the collective interactions between many self-directed individuals, or agents. One fascinating aspect of phenomena such as these is that very complex system behaviors and patterns can emerge from agents interacting with one another according to a relatively simple set of rules and often unaware of the consequences of their actions in the overall scheme of things.

Evolutionary structural optimization (ESO), Bidirectional evolutionary structural optimization (BESO) and Soft Kill Option, (SKO) are structural optimization techniques based on nature's techniques effective utilization of structural materials. Examples will be discussed in greater detail later in this report.

Figures 25 and 26 were created from systematic studies made using the VisualBots for Excel educational type tool[23] to illustration the general nature of some of the some of the biological optimization methods when applied to "traveling salesman problems" which involve determining the shortest distance continuous route between a set of destinations.

Figure 25 shows the numbers of iterations of the design parameter sets that were required to achieve the optimum solution for ten repeated optimizations for each of three biological optimization methods. These include ant colony optimization (AC), genetic algorithms (GA) and simulated annealing, (SA).



Finding the Solution

No of Iterations to Optimum(= 377.064)			
Case	Ant Col	GA	SA
1	190	185	4039
2	57	206	4194
3	143	163	[405]
4	190	207	4903
5	201	294	4284
6	185	160	4666
7	136	193	4852
8	83	248	5275
9	159	247	4571
10	146	225	4052
Mean	149	213	4537

Fig. 25. Comparison of Biological Optimization Methods Solutions

The above results show that the various optimization methods were not equally effective in determining the best solution and that the number of Iterations to convergence is often random.

Figure 26 shows the rate of convergence for the three optimization methods when applied to another traveling salesman problem for which the optimum solution is once again known.

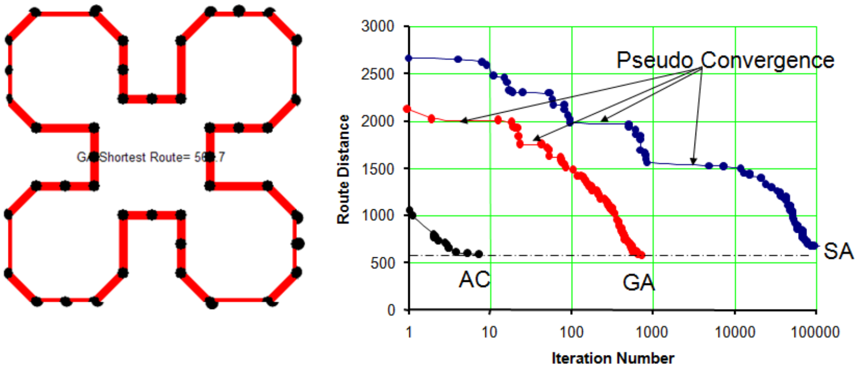


Fig. 26. Another Traveling Salesman Problem

In this example it is seen that the number of iterations necessary to achieve the known optimum solution varies by orders of magnitudes depending on the optimization algorithm. The SA method never actually "found" the optimum solution. The solutions also indicate regions of pseudo convergence which could have been interpreted as finding an optimum if the optimum solution had not been known.

Figure 27 illustrates how unexpected fundamental concepts can arise from robust configuration optimization using genetic algorithms, GA. In this example [24, 25, 26] 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.

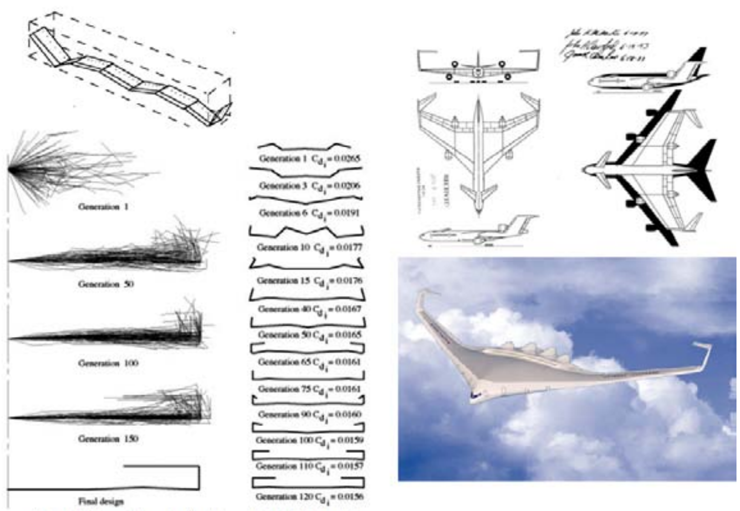


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Figure 27: Neo-bionic Innovative Configuration Development

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 27. 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 study[11] is shown in figure 28. 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.

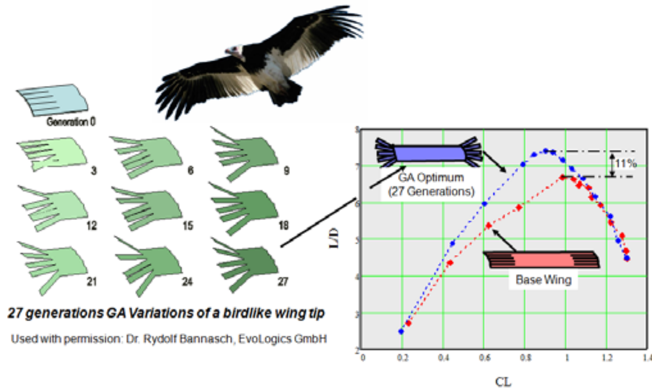

Fig. 28. GA Evolutionary Optimization of Slotted Wing Tips in the Wind Tunnel

The evolutionary structural optimization (ESO) method[27] 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 29 shows the results of an ESO study to determine the optimal shape for an object hanging in the air under its own weight. An initial square model is shown on the left. Before the ESO procedure is applied, two slots have been cut at the top in the initial model to create a stalk. The top end of the stalk is fixed. The only loading on this object is the gravity. By removing least stressed material from the surface, we obtain shapes with uniform stress on the surface. The results are similar to the shape of certain fruits such as apples and cherries

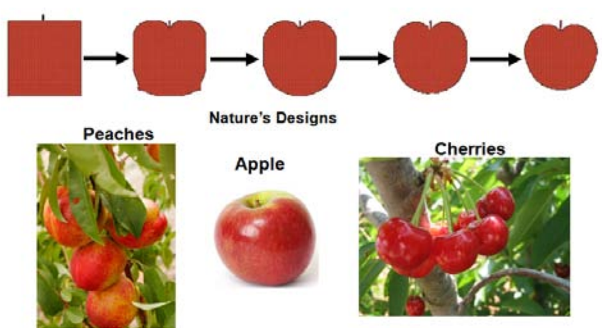

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Fig. 29. : Optimal Shape for an Object Hanging in Air Under its Own Weight

Figure 30 hows the use of the BESO algorithm in the design of 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 intermediate geometries leading to the optimum stool design.

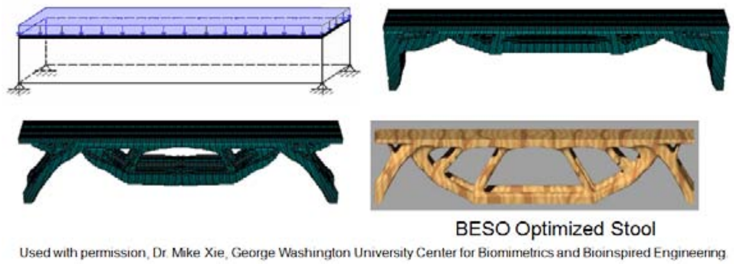


Fig. 30. BESO Optimized Stool Design

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 Trees [28], Prof. Mattheck introduced what he called the Principle of Constant Stresses derived from analogies observed in the growth of trees [29]. 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 processes[30]. In the case of a car door, it has been reported that 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 would be 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.

VII. "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 31 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 Proteus[1] 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 on its a biplane-like wing configuration to swoop from tree to tree.

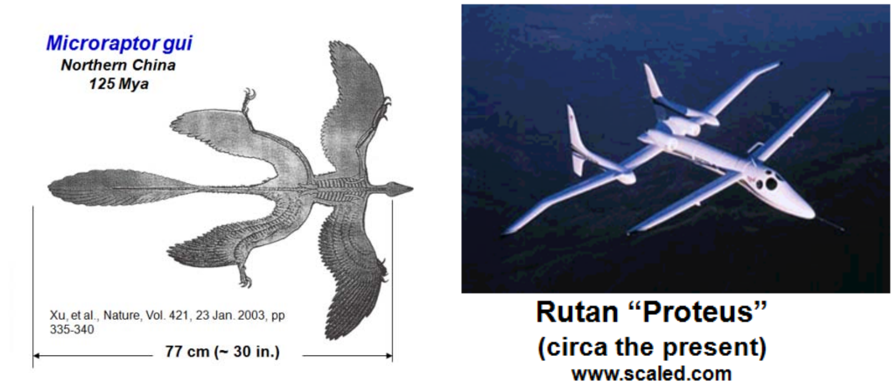


Figure 31: Tandem Wing Fliers

Figure 32 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 noise[31]. The owl has a number of additional low noise evolutionary developments since stealth is critical to its survival.

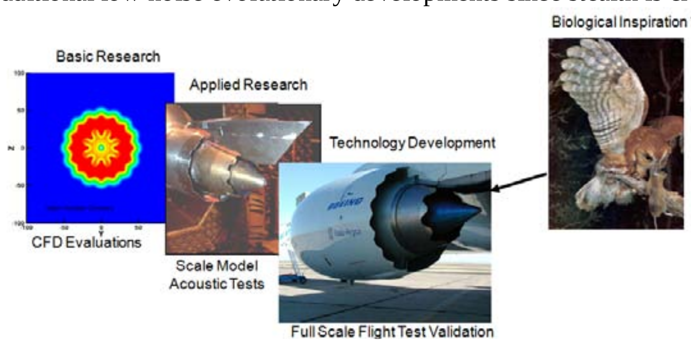


Fig. 32. Acoustic Noise Reduction

Figure 33 shows an number structural and material concepts borrowed from nature including the warren truss design that nature applied in the sandwich structure in a bird wing, the skin stringer type structural evident in a damsel fly wing, honeycomb structure of a wasp nest and strong impact resistant materials as used in a abalone shell.

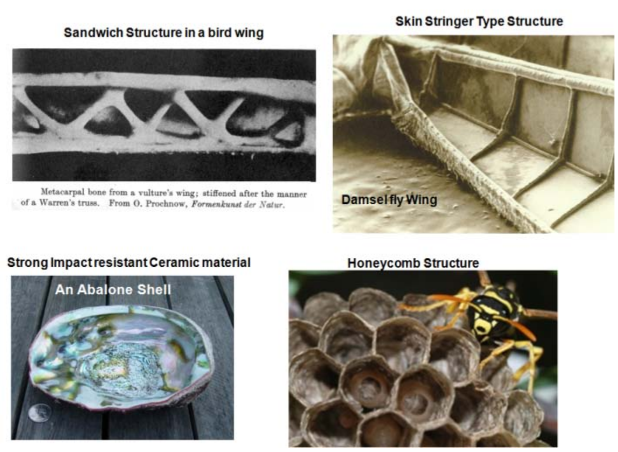


Fig. 33: Borrowed Structural Concepts & Materials From Nature

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 34, 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 landing[32].

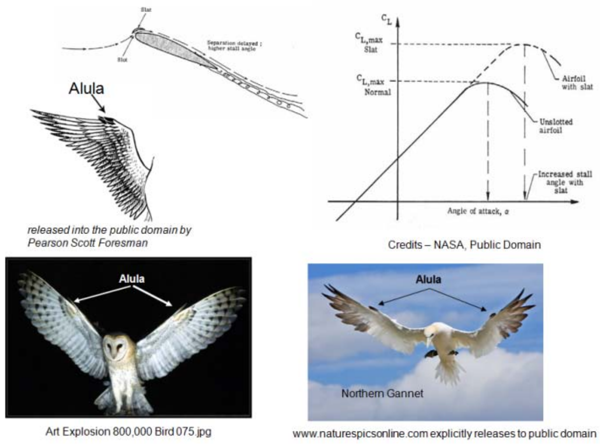


Fig. 34: Alula- Natures Leading Edge Slats

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.

As shown in figure 35, 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 (figure36). 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.

Fig. 35 Nature Did Invent the Wheel

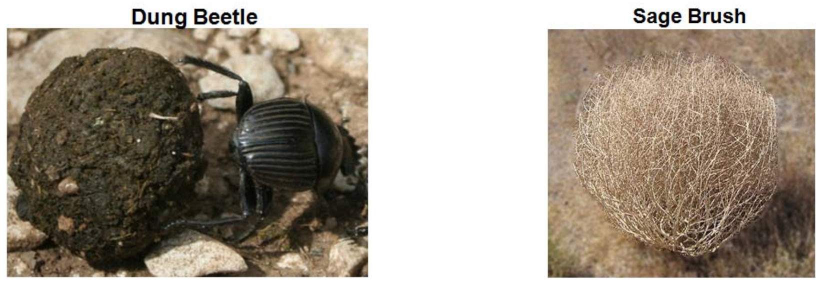


Fig 36: More of Nature's Rollers

A species of mantis shrimp, the stomatopod crustacean Nannosquilla decemspinosa, if washed onto a sandy beach by a wave will immediately roll back to the water by means of consecutive backward somersaults effectively forming a wheel with its entire body, as shown in figure37. In a sense, it can be said that nature also invented the continuous track used on many of our specialized vehicles

Fig. 37. Nature Invented the Continuous Track Wheel

VIII. "CYBERNETICS" AS A SOURCE FOR DESIGN INSPIRATION

Cybernetics will be defined here in 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 38 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 could then be applied to the development of an artificial flying insect. This fundamental approach for cybernetics is illustrated in figure 38.

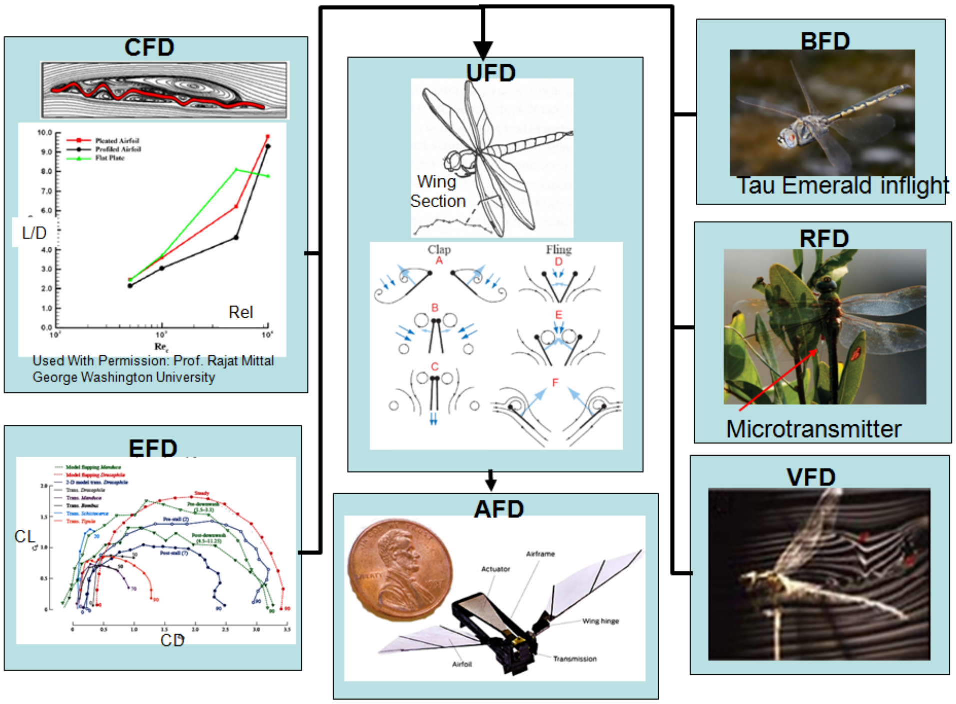


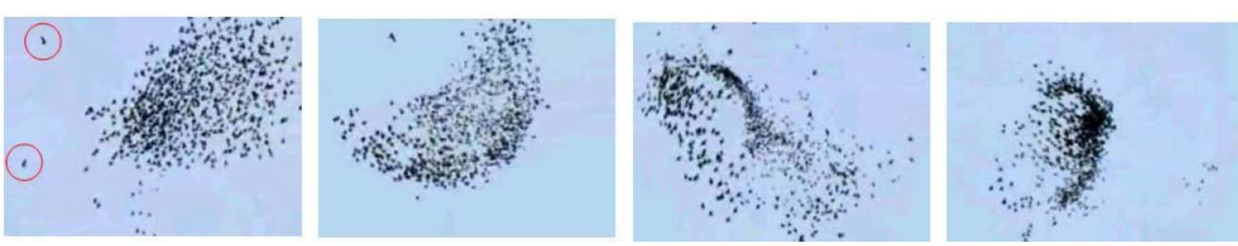
Fig. 38. Integrated Approach to Reverse Engineering of Nature

Many have observed at various times the magnificent aerobatic displays of large flocks of birds as shown in figure 39, 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 cooperating 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 systems[33]. The individual (but autonomous) agent does not follow directives from a central authority or work according to some global plan.

For 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



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

Figure 39: Bird Swarms and Group Dynamics

Craig Reynolds, a computer graphics researcher, in 1986 created a deceptively simple steering program called boids[34]. 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.

Flake [26] 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 39 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 40 shows lifted covert feathers on a brown skua and also 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 studies[35] 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 airfoil.

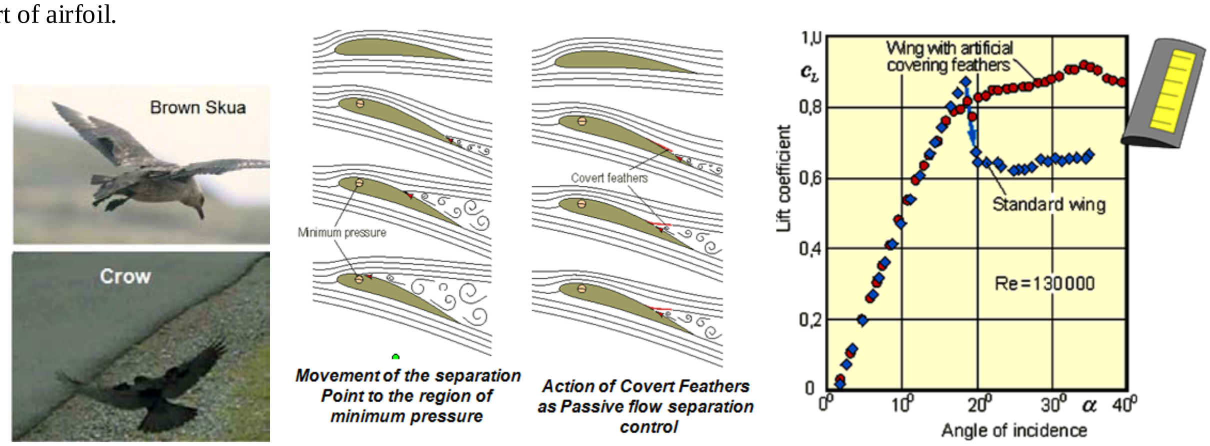
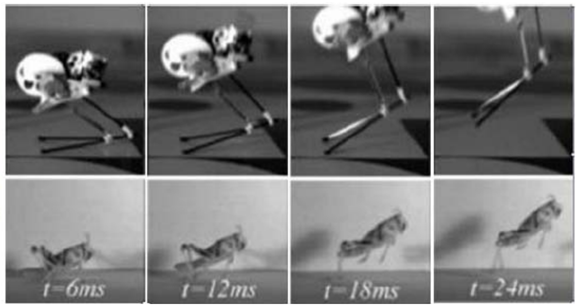
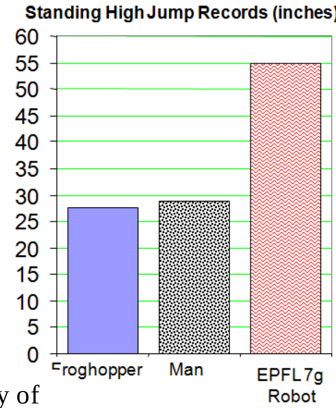


Fig. 39. Covert Feathers as "Eddy Flaps"

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 40. 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.
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.

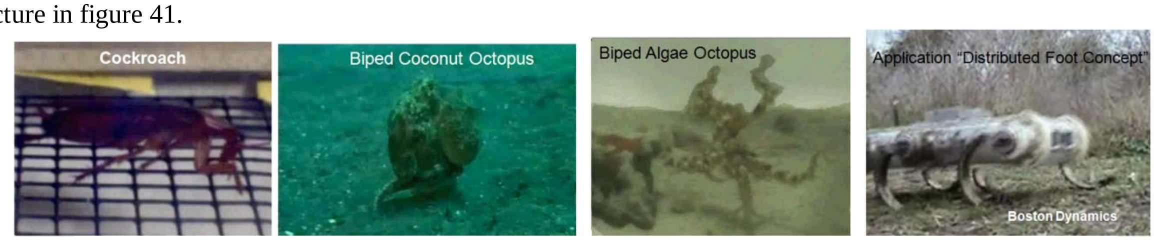




Images Courtesy, Professor Dario Floreano, Laboratory of Intelligent Systems, Swiss Federal Institute of Technology

Fig. 40. 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 41.

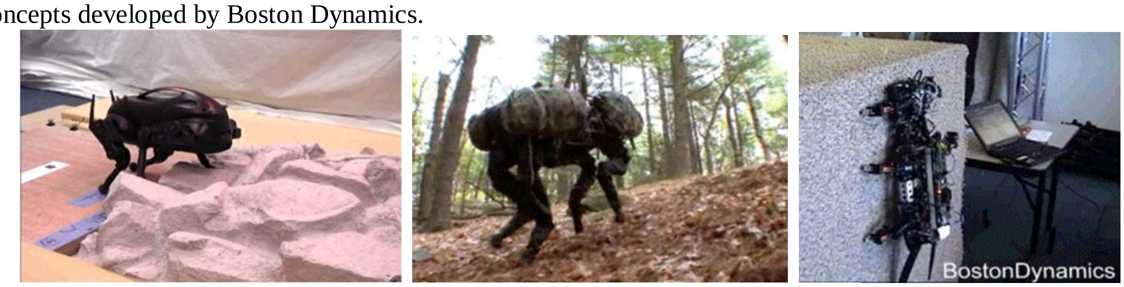


Courtesy of Dr. Robert Full, University of California, Berkeley, Department of Integrative Biology

Fig. 41 Natures Distributed Foot.

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 41, 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 42 shows a series of nature inspired mobility concepts developed by Boston Dynamics.



Images courtesy of Boston Dynamics, ©, 2009

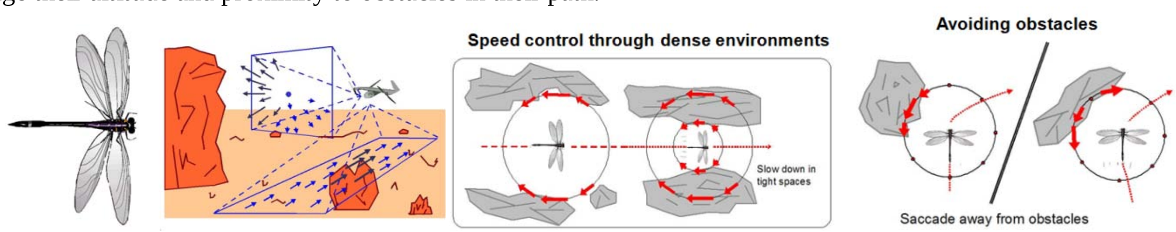
Fig.42. Other Nature Related Mobility Concepts

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 has an on-board computer that controls locomotion, servos the legs and handles a wide variety of sensors. 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.

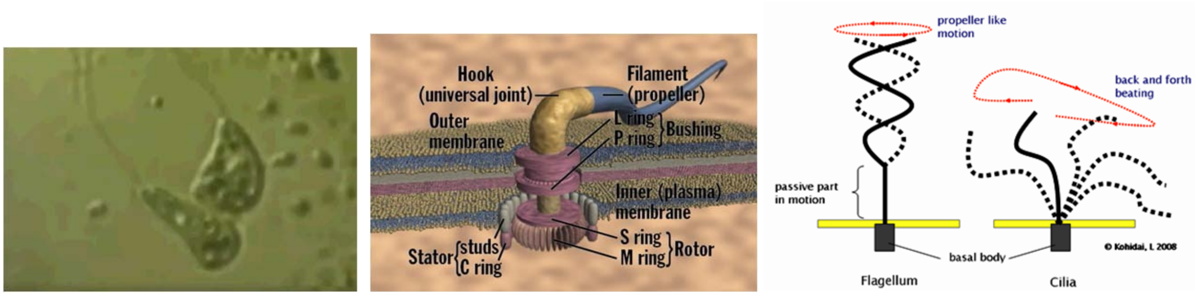
Insects such as the dragonfly utilize optic flow in order to navigate in and around obstacles as shown in figure 43. The term "optic flow" refers to a visual phenomenon that you experience every day. Essentially, optic flow is the apparent visual motion that you experience as you move through the world. 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. 43. Dragonfly and Optic Flow

Nature created an incredible self assembly high speed reverse direction rotary motor with a diameter of 30 nm shown in figure 44. Mobility of bacteria, such as Salmonella and E. coli with a body size of 1 ~ 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 thatgrows 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



Permission Granted: Dr. K. Namba, Protonic NanoMachine Group, Osaka University

Fig. 44. Nature's Rotary Engine

IX. "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

The famous US Aerodynamicist Dr. Robert T. Jones once said *"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 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 Minimum Wave Drag Nose
- Supersonic Favorable Interference Concepts
- Low Sonic Boom Concepts

The concept of the near sonic area rule shown in figure 45 as an example of arriving at an innovative aerodynamic concept or discovery by various individuals who followed independent paths to discovery while using predominately different aerodynamic tools[36].

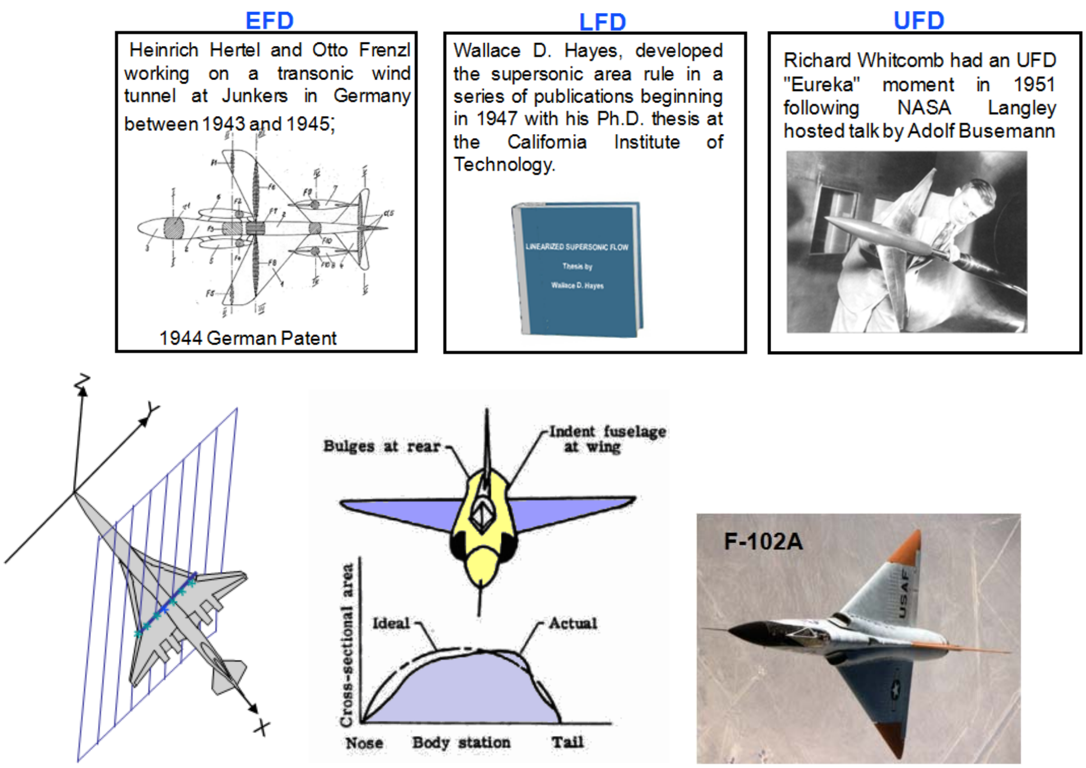


Fig. 45. Various Paths Leading to the Development of the NACA Area Rule

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 the 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 45 show results of the first full scale of the NACA area rule to the F-102A.

Figure 46 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 edges[37]. 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, RSA[38] 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,.

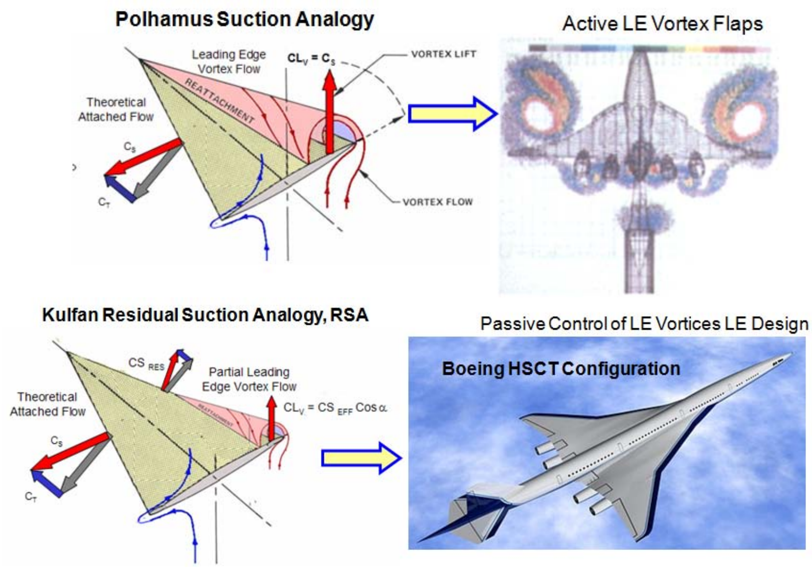


Fig. 46. Use of SFD Plus UFD to Develop Vortex Control Concepts

Figure 47 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, EFD and UFD.

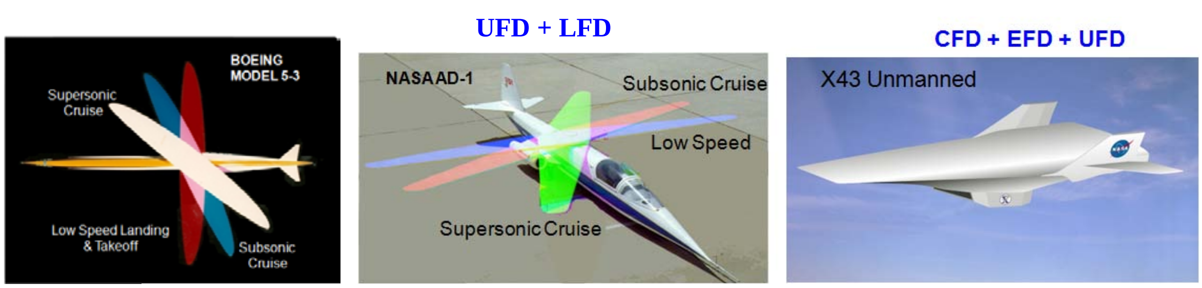


Figure 47: Examples of Aircraft Concepts Having No Parallel in Nature

The laminar flow control technology shown in figure 48 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.

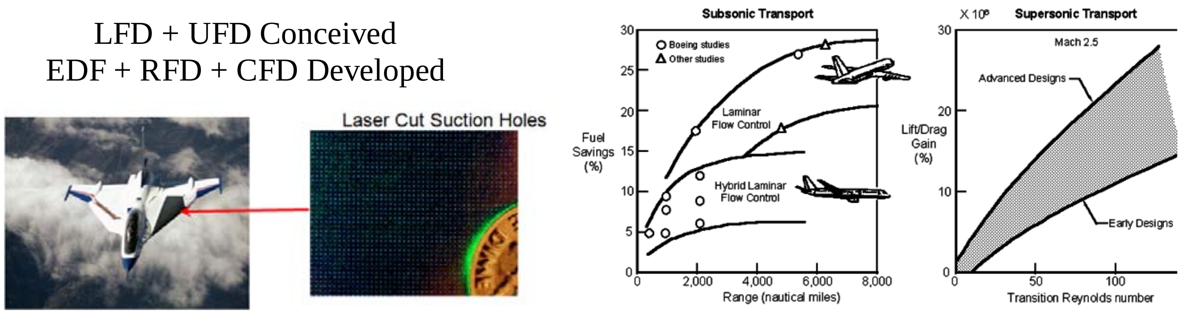


Fig. 48. Aircraft Laminar Flow Control, LFC, Technologies

X. IDEAS ARE EVERY WHERE

Ideas for innovation are everywhere as shown in figure 49 for some of the biologically inspired innovations that we have previously discussed.

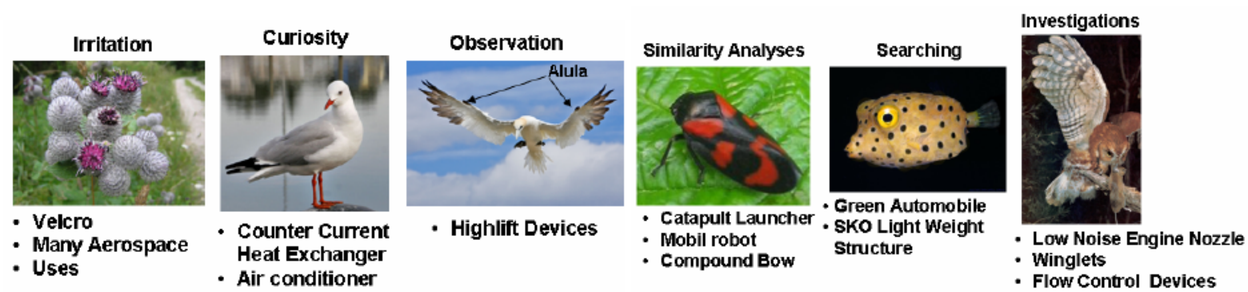


Fig. 49. Ideas Are Every Where – What have we seen?

What do you see in Fig. 50? 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 whaleflipper 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 lays 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 indicated in the figure.

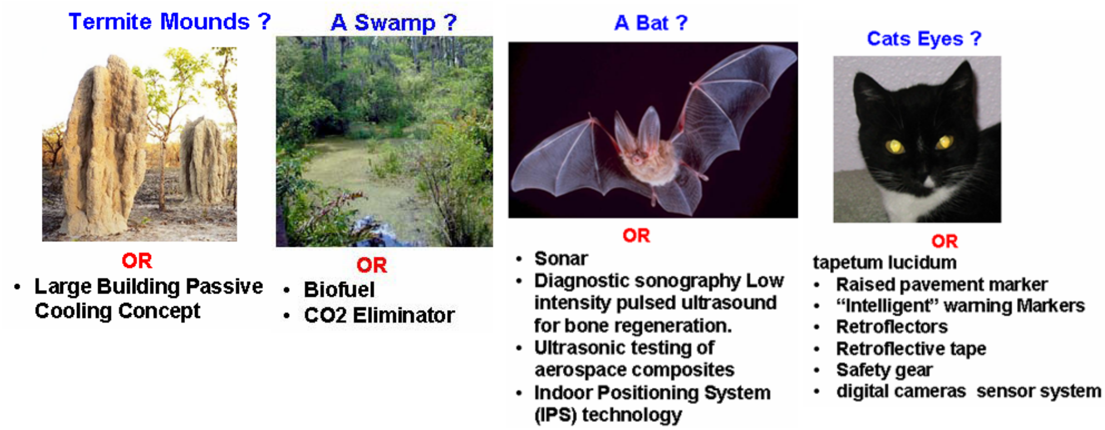


Fig. 50. Ideas Are Every Where – What do You See ?

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 51, 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.

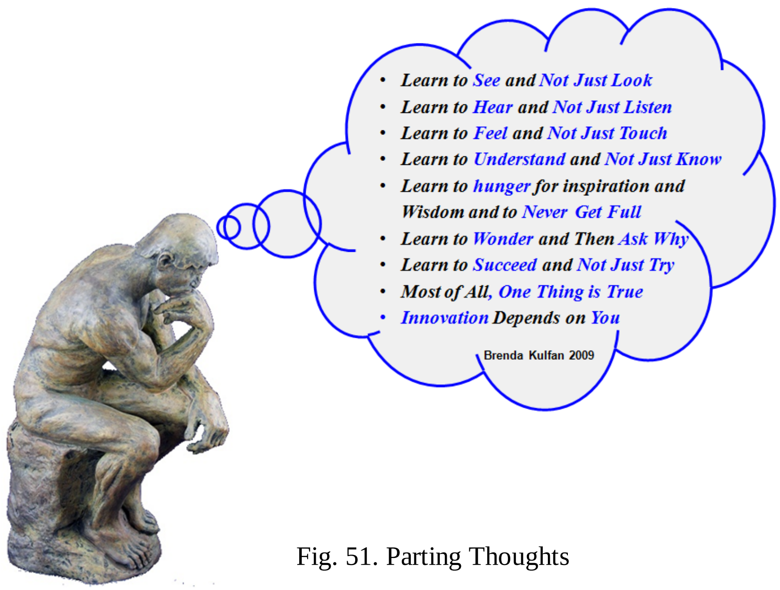


Fig. 51. Parting Thoughts

As shown if figure 51, the key to innovation is you. Be excited: There are many more problems to solve, concepts to create and flying vehicles to develop.

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