Gateway Engineering Education Coalition

Discovering the Principles of Design Through Reverse Engineering

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DISCOVERING THE PRINCIPLES OF DESIGN THROUGH REVERSE ENGINEERING

I

LEONARDO AND HIS FLYING MACHINE

THE IMPORTANCE OF CLEAR CONCEPTS AND ANALYSIS

In the late 1400's and early 1500's Leonardo was thinking about flight and flying machines. He recorded his thought in numerous sketches which we can still admire. It does not appear that he built any of the devices he contemplated, however.

That is perhaps just as well, since he might have shortened his life span considering the fact that none of them could sustain flight.

With the wisdom of hindsight and the accumulated experience of five centuries of discoveries, inventions and know-how in the natural sciences, mechanics, aeronautics, material science, engineering and other arts and sciences, it is easy for us to see how and why Leonardo failed. This does not detract from his achievements. But failure is a great teacher for engineers and this illustrious failure may give us a clue as to what may make for a successful design.

When Leonardo was working, the concepts force, acceleration and mass had yet to be formulated. It would take another two full centuries before such towering giants such as Galileo and Newton clarified these concepts and established their fundamental relationship.

Watching the flight of birds is fascinating: such elegance, grace, effortlessness and apparent simplicity--a naturalness which invites us to think that if we could just imitate nature our problems would be solved. But nature had millions of years to experiment! From dinosaurs to eagles, how many byways in the labyrinth of evolution?

The point is that the number of functions performed by a bird, such as the humble pigeon for example, regarding flight alone, are incredible. How clumsy and inefficient in comparison seem our flying machines, helicopter and air liners and even our fighter aircrafts.

Think of the number of apparently contradictory functional requirements embodied in a pigeon! To take off and land with initial speed on anything from the ground to a wire; a roof top or a tree; to move at will in the six directions of space within a wide range of speeds; to refuel in flight (eating insects); head home from hundreds of miles away without an expensive satellite guidance system; drawing its energy from an occasional handful of unprocessed grains and a sip of water picked along the way and producing entirely recyclable waste. All this packaged in a system weighing less than a third of a kilogram, and operating in virtual silence!

Think of the delicate balance and the interaction between the various functional requirements: range and energy requirement, maneuverability and stability, guidance and range, energy requirement and maneuverability, etc., etc.

To set out to imitate nature without first thoroughly understanding the complexity of the fundamental requirements (and their relationships) that nature puts on its systems is therefore more than likely to be unrewarding for the designer.

In its simplest formulation, flying requires lifting a load from the ground against the field of gravity and moving it in a specified direction. Our pigeon can do this by just beating its wings. Leonardo's flying machine could achieve neither. Fascinated by the movement of the bird's wings and caught in their complexity, Leonardo did not clearly distinguish between these two separate requirements.

The first successful attempt to get off the ground by man was achieved by the Montgolfier brothers in the eighteenth century with their hot air balloon. They concentrated on one single factor: get off the ground. It was a daring thought that captured the imagination of kings and peasants alike: riding a cloud of smoke hanging from a papier maché globe!

So gravity was overcome, lift was achieved. But what about direction? Our aeronauts were left to drift with the wind.

It would take another daring soul: Giffard in 1852, and the availability of a "light" steam engine to provide power for propelling our gravity defiant balloons in a given direction.

The experiment of the "dirigible" balloon clearly established the distinction of the main functions to be satisfied for flight: lift and thrust to overcome weight and drag respectively.

The bird combined these two functions so skillfully in the gracious and powerful movement of its wings that it is difficult to separate them by observation alone. The problem has first to be simplified and reduced to its simplest expression compatible with a possible technical solution. As importantly, concepts as elementary and fundamental as mass, force, work, power and their relationships have to be available.

Had this been known to Leonardo, he would have realized the futility of his designs. We might also have been deprived of his musings and beautiful drawings.

Generating enough lift and thrust for a given mass to move through the air under its own power requires comparatively high power. From that viewpoint, the power-to-weight ratio of a bird is considerably higher than that of a man, making certain things feasible for a bird that are more of a challenge for a human being.

Generating lift *and* thrust in a specified ratio at the same time by wings is also a considerable challenge. Separating these functions: letting wings do the lifting and a propeller or a jet the thrusting begins to make things manageable, at least conceptually.

Of course, the two could later be recombined as in the case of the rotor in a helicopter that ensues both lift and thrust by proper adjustment of the blade orientation. Yet, even here, stabilization must be provided by a second thrusting device to avoid a counter rotation of the fuselage itself. Thus, the ability to maintain the independence of the functional requirements, of lift and thrust, by design, made designers free to build fixed wings that would generate adequate lift if the relative air velocity was adequate. It also let them free to build "screws," "propellers" or jets that would provide sufficient thrust to overcome the drag caused by movement though air.

Ideally, therefore, each functional requirement (lift or thrust) would be controlled by a corresponding design parameter and a symbolic equation written:

$$FR_1 = a_1 \quad DP_1$$

$$FR_1 = a_2 \quad DP_2$$

Or more generally

$$\begin{bmatrix} FR_1 \\ FR_2 \end{bmatrix} = \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix} \begin{bmatrix} a_1 & o \\ o & a_2 \end{bmatrix}$$

So that, for example, changing the design of the propeller (DP_2) should affect the thrust only (FR_2) but not the lift, (FR_1). Similarly changing the design of the wing (DP_1) should affect only the lift (FR_1) but not the thrust (FR_2).

But in fact the lift L is generated by the forward motion caused by the thrust T so that they are physically related. It is the function of the designer to insure that, within a certain range, Thrust and Lift are uncoupled. The use of certain control surfaces provides a solution. Let us now run a little calculation to see why Leonardo could not succeed in spite of his ingenuity.

In level flight, without acceleration, the lift just overcomes the weight, (L = W) and the thrust just overcomes the drag produced by the forward motion on the body (T = D).
Lift is desirable but drag is not, so that the job of the designer is to maximize the ratio.

The higher this ratio, the less power is needed for the flight. The ratio can conveniently be measured in a wind tunnel on models:

for birds: $$6 < \frac{L}{D} < 25$$

for aircraft: $$10 < \frac{L}{D} < 40$$

Some moderately aerodynamic bird and commercial airliners have comparable $\frac{L}{D}$ ratios.

$$\frac{L}{D} \cong 15 \qquad (1)$$

For a quick, "back of the envelope" calculation to give us an idea of the order of magnitude of the factors involved, consider a small pigeon mass = 0.3kg.

Its weight is approximately: $w = 10x\ 0.3 = 3N$

(Here 10 m/s^2 is taken as a round figure instead of 9.81 for the acceleration of gravity).

In level flight, weight and lift are equal so that:

$$W = L$$

and, from equation (1)

$$D \cong \frac{L}{15} = \frac{W}{15} = \frac{3N}{15} = 0.2N$$

For a speed of flight of 15 m/s

i.e., 15 x 3600 = 54 km/h ≅ 33 mph

The power required is: $Power = \frac{work}{unit\ time} = Force\ x\ velocity$

$$= 0.2N \times 15m/s = 3Nm/s = 3Watts$$

Our pigeon has therefore a Power to Mass ratio of:

$$\frac{3}{0.3} = 10\ w/kg$$

Leonardo's flying machine evidently remained at the conceptual level. He never settled on a particular design. The models which have been built are therefore rather in the nature of creative reconstruction than of careful reproduction, piecing together comparable solutions form various pages of his notes and consistent with Leonardo's own technology and inventive process.

James Wink of Tetra Associates, London, built such a model in 1988.(*) Using the kind of materials that would have been available to a sixteenth century designer, wood for the framework, leather for joints and thongs, steel or cow-horn for springs, starched taffeta cloth for the skin, the estimated weight of the full scale model comes to 650 lbs. or 295 kg. If we add to this 70kg (155 lbs.) for the flyer, we come to a grand total of 365 kg (805 lbs.).

Consider a man/machine combination with such a mass. Assuming a performance comparable to our pigeon, one would require 3650W or 3.65 kw, i.e.- (4.89 HP) for the power to be developed by the flyer.

An average man at full power can deliver about 1/3 HP for a short time.
Since 1 HP = 75 kg-m, this amounts to lifting 25 kg (55 lbs.) from the ground onto a table 1 meter high (3 1/3 feet) every one second. Our flyer would need 15 times that amount of power to fly the machine assuming no energy losses. i.e., a 100% efficient machine.

The efficiency is defined as the ratio of useful output power to the input power:

$$efficiency = \frac{useful\ output\ power}{input\ power}$$

Being generous, the efficiency of Leonardo's wooden mechanism with its wooden levers hinged on leather straps rubbing on wooden fulcrums, wooden pulleys rotating on wooden shafts, ropes sliding in wooden guides and so on, would not be lighter than 50% and probably much less, i.e., about half or more the available energy would be dissipated in friction as heat going to the atmosphere. Therefore only half or less the available energy could be used for thrust and lift.

Given the fact that the flapping wing efficiency for birds is the order of 40%, the somewhat less sophisticated design of Leonardo would not exceed 30% so that the useful energy would be further reduced. The power required of the person manning Leonardo's machine would therefore be:

$$\frac{3650}{0.5 \ x \ 0.3} = 24{,}333W \quad or \quad 32.62/hp$$

This man would have to have the strength of 100 men!

Yet recently Paul McCready designed the Daedalus 88, a flying machine that flew 74 miles over the Aegean Sea in April 1988, entirely under human power. How did he do that?

First, through fine aerodynamics: His Lift to Drag ratio is the order of 50 rather than 15 so that the power requirement is now 15/50 = 0.3 of what it was in our example.

Second, by increased efficiencies (propeller versus wing flapping and reduced friction). Assuming as a first approximation 90% and 98% respectively for each, the overall efficiency in now 0.90 x 0.98 = 0.882

i.e. 88.20% rather than 0.5 x .3 = 0.15 or 15%.

i.e., an increase by a factor of $\frac{88.2}{15} = 5.88$

Third, by choosing high-tech, light and strong materials rather than natural materials such as wood, cloth and leather, thereby increasing the power to mass ratio.

Daedalus 88 weighs 72 lbs. or 227 lbs. with its pilot. The power to mass ratio is therefore increased by a factor of $\frac{805}{227} = 3.55$

The total output required of the pilot is now:

$$\frac{32.62hp \ x \ 0.3}{3.55 \ x \ 5.88} = 0.47hp$$

This is still high, but assume that Leonardo's machine had a lift-to-drag ratio as good as a pigeon. This would certainly not be the case. Assuming half of that figure as more realistic, our pilot would have to supply 0.23hp which is what a good athelete can produce for a reasonable amount of time.

What lesson then do we draw from Leonardo's failure?

First: *The importance of clearly established scientific principles.* Newtonian mechanic was as not yet in the days of Leonardo, nor were the concepts of force, work, power, efficiency well defined as entities. Fluid mechanics did not exist, nor material science.

Second: *The importance of clearly defined functional requirements* (FR's) such as Lift and Thrust in this case.

Third: *The importance of being able to translate functional requirements into Design Parameters through imaginative solutions* (wing flapping for Leonardo, balloon and propeller for Giffard, fixed wing and propeller for the Wright brothers).

Fourth: *The importance of keeping within a practical range the independence of the functional requirement through the design process* so that each FR has its own separate handle (Design Parameter, DP): Changing the propeller design does not affect the Lift, nor changing the wing design, the thrust. If changing the propeller design would affect the Lift adversely, we would be led to redesign the wing to get proper lift, but this might in turn affect the drag and therefore the propeller design which, in turn, would affect the lift. We would thereby be let into a spiraling iteration which would not necessarily end in a happy compromise.

Fifth: *The importance of analysis and calculations* to establish the "design space" or "envelope of feasibility."

Sixth: *The importance of a tight feedback loop between analysis and synthesis*, one informing the other.

Seventh: *The importance of keeping the design simple*: the less "Rube Goldbergy," the less opportunities for breakdowns and inefficiencies! (Fix wings and separate thruster versus wing flapping). This is another aspect of the principle of economy met with in design theory: very briefly, the simpler the explanation, the more likely. Shades of William of Ockman and his razor!

Having discovered some basic design rules ghrough the analysis of an artifact in this case Leonardo's flying machine, we begin to appreciate what design is.

We could define it as:

"A process through which specific parameters are determined satisfying clearly conceived functional requirements."

This is sometimes described as a "mapping" from the domain of the functional requirements onto the domain of the design parameters. More fundamentally perhaps we can see it as *"a specific set of rules for the purpose reordering of the elements of the environment to satisfy a certain purpose."*

Man-powered flight apart, the availability of new materials such as plastics and cheap manufacturing techniques has made building a flying mechanical bird child's play these days. No doubt, Leonardo would have delighted in this toy now on the market: a pair of wings flapping under the power of a simple rubber band mounted into a pigeon-looking body.