Toward Indoor Flying Robots

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Abstract

Developing a research autonomous plane for flying in a laboratory space is a challenge that forces one to understand the specific aerodynamic, power and construction constraints. In order to obtain a very slow flight while maintaining a high maneuverability, ultra-light structures and adequate components are required.

In this paper we analyze the wing, propeller and motor characteristics and propose a methodology to optimize the motor/gear/propeller system. The C4 model plane (50g, 1.5m/s) demonstrates the feasibility of such a laboratory flying test-bed.

1. Introduction

After years of research on rolling and walking robots, why not moving to flying robots? The dynamics and thus the navigational possibilities and requirements of such vehicles are fundamentally different from terrestrial robots. This may lead not only to interesting behaviors but also to new kinds of controller schemes.

A number of projects already exist with airborne test-beds like remote controlled helicopters [1], planes (e.g. the military drones [2-3] or the well-known micro air vehicles, MAVs [4-7]), or airships but most of them are outdoor machines, consequently requiring large teams, considerable technical skills and significant budgets. It is to notice that very few of them are really autonomous devices.

For these reasons, doing outdoor flying robotics is too heavy for most of the research teams. Therefore, we propose to investigate the possibility of indoor flying. We believe that if an inexpensive laboratory flying test-bed is feasible, this field may become very appealing for many researchers.

The flying schemes can be classified into four categories: lighter-than-air, flapping wings, rotary wings, and fixed wings. All of them are not convenient for indoor use.

Airships or blimps are probably the easiest way to make a robot fly. The envelop size can be adapted to the payload (a 1m diameter sphere filled with helium can approximately lift 100g). Powered with three or more DC motors, they are quiet and not dangerous. Provided with ingeniously arranged protections, they can bump into obstacles without damage. No in-depth knowledge in aerodynamics is required to build such a machine. Consequently, some robotic research teams already adopted this option [8-9]. The drawbacks of the blimp are its inertia associated with its quite important volume and the need for helium.

A **flapping wings** hummingbird is the dream for many researchers. Sustained flight has been demonstrated [10], but full control with a payload in an indoor environment is not for tomorrow. However, flapping wings represent the only hope to reduce the size below 10cm wing span, and quite interesting projects are currently in progress [11], backed by serious fly studies [12].

Helicopters are most likely too dangerous and noisy. In general, R/C helicopters tend to be heavy and expensive. However, the lightest indoor R/C helicopter [13] weighs only 50g, and even much smaller ones are considered by scientists [14]. But they may be too fragile, too sensitive to payload, and have very limited running time.

Hence it seems that autonomous indoor **planes** are an essential step toward the mastering of flying robots. The technology is partly available from indoor hobby plane suppliers and clubs (WES Technik, DIDEL, Aeronutz, RCmicroflight, Ezonemag).

This paper presents the essential elements for the modeling and design of an indoor fixed wings flying robot, with very low flight speed and adequate maneuverability for operation in a 10x10m room. First some principles of basic aerodynamics are summarized and the correspondence laws are applied to get some clues on what happens with small dimensions and low speed. Then the wing, propeller, and motor design are tackled. Finally some thoughts about the weight distribution and the navigation control are given.

2. Basic Aerodynamics

Lift and drag are generated by the wing or propeller moving in the air [15-16]. If ρ is the air density (about 1.22kg/m^3 at 20°C, at sea level), S the wing area and v the relative air speed, then the lift F_L and drag F_D are given by

$$F_L = \frac{1}{2}\rho C_L S v^2 \cong 0.61 \cdot C_L S v^2 \qquad (1)$$

$$F_D = \frac{1}{2}\rho C_D S v^2 \cong 0.61 \cdot C_D S v^2 \qquad (2)$$

The polar plots (figure 1) display the C_L and C_D parameters at different angle of attack. These coefficients also depend on the airfoil shape and the kind of airflow around it, which is determined by the Reynolds number *Re*:

$$Re = \frac{\rho L v}{\mu} = \frac{\rho v^2}{\mu v / L} = \frac{inertia}{viscous} \cong 68000 \cdot Lv \qquad (3)$$

μ is the air dynamic viscosity ($1.8 \cdot 10^{-5}$ kg·s^{-1}·m^{-1} at 20°) and L a characteristic length of the airfoil (in general the wing chord). *Re* represents the ratio of inertial to viscous forces.

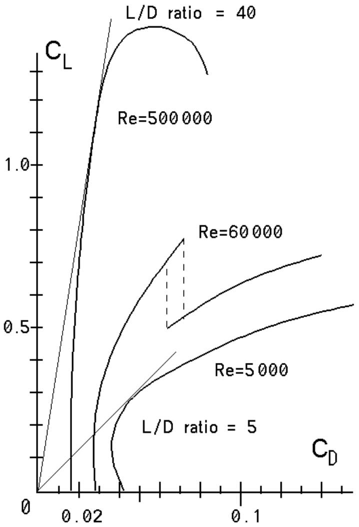

Figure 1: *Typical polars for an airfoil at different Re*

If the aerodynamic is good for large planes, it deteriorates rapidly for the small planes we are interested in [16-17]. Below a critical *Re* of about 50000, the viscosity influences the micro-turbulent flow against the surface, bubbles appear that break the lift, and the drag increases significantly. The lift to drag ratio (fineness), which is easily better than 40 for a modern glider, gets down to 3 to 5 for an indoor plane with a small aspect ratio. At *Re* smaller than 1000, different aerodynamic principles have to be used: the flapping wings of hummingbird and insects create vortices on which the wings lean against [12].

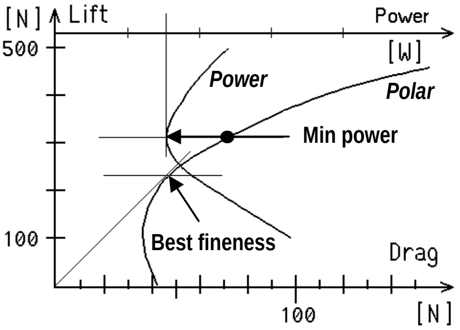

Figure 2: *Best gliding and power ratio*

In general, for indoor flying robots, the best lift/drag ratio is not exactly what we are interested in, but rather minimum power dissipation. This is the case if the ratio F_L^2/F_D^3 is minimal [15]. Figure 2 shows the C4 model plane [18] polar measured in a wind tunnel at 1.5m/s. In the same graph, the power curve is shown. Its minimum (in horizontal) gives the lift for minimum power.

For horizontal flight, the lift compensates exactly the weight W (F_L=W). The wing loading σ is an important parameter:

$$\sigma = W/S \qquad (4)$$

$$W = F_L \cong 0.61 \cdot C_L \cdot S \cdot v^2 \qquad (5)$$

For our plane, minimum power is required, in order to increase the flight time for a given battery.

$$P = F_D \cdot v = 0.61 \cdot C_D \cdot S \cdot v^3 \qquad (6)$$

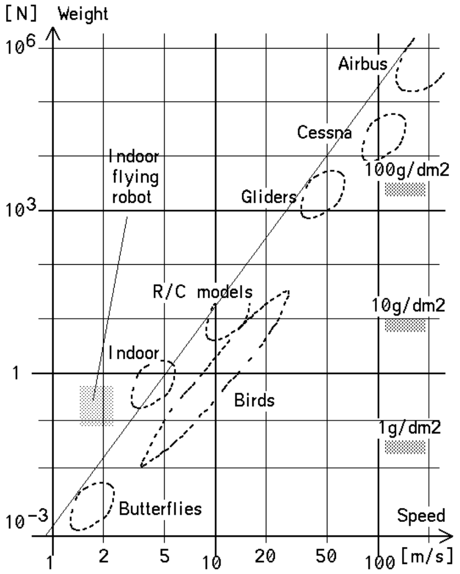

Figure 3: *Aircraft weight vs speed*

Flying at minimal power requires the lowest possible speed. This implies large wings and very low weight.

What is realistic? Planes, birds and insects have developed minimal weight, reliable technologies, which are approximately plotted on figure 3. We conclude that a 50g, 1.5m/s plane is possible, but pushes the boundaries of the usual construction techniques.

For existing flying objects, S and v are linked by the plot of figure 3. The empirical value of the speed v is related to the weight as follow:

$$v \cong 5 \cdot \sqrt[4]{F_L} = 5 \cdot \sqrt[4]{W} \qquad (7)$$

This formula does not result from similitude laws, but from nature evolution and engineers solutions taking care of manufacturing and energetic factors.

For a given weight, similitude analysis [19] shows that the lift F_L is proportional to Sv^2 (formula 1):

$$F_L \propto Sv^2 \propto L^2v^2 \qquad (8)$$

L is a reference dimension and v the speed. The drag is also proportional to Sv^2 (formula 2), and the power P for a horizontal flight is proportional to Sv^3 (formula 6):

$$P \propto L^2v^3 \qquad (9)$$

For a given weight (formula 5):

$$S \propto 1/v^2,\ L \propto 1/v, \text{ or } v \propto 1/L \qquad (10)$$

If the plane is twice as large for the same weight, it will fly two times slower.

We are more concerned with the power:

$$P \propto L^2v^3 \propto 1/L \qquad (11)$$

The twice larger plane will need half the power, but again, this assumes the same weight.

3. Wing Design

For a 50g indoor plane (included 20g of payload for sensors and microcontroller), it is worth to stay below 3g/dm^2 wing load, that is about 20dm^2 (80cm span and 26cm chord length. Because of other heavy components (batteries, motors), the weight of the wing should be less than 5g. A good method for the construction of such a wing is to employ carbon rods for the frame and a thin plastic film for the cover, as used for the C4 model (figure 11). A realization that would respect a given documented airfoil is too heavy, supposing one has the data for that airfoil measured at the corresponding *Re* number.

The shape of an ultra-light airfoil is given in figure 4. Gluing the film on the leading edge will result in burrs which may have a positive effect. Actually, the laminar flow is good for drag, but bubbles and then vortices will form easily with the lift suction. Creating some micro-turbulence is probably favorable, but extensive tests in a wind tunnel are still required to understand the phenomena and find the best light-weight shape. It is not easy to find a wind tunnel with the very low speed we are interested in and having sensitive enough aerodynamic scales [17].

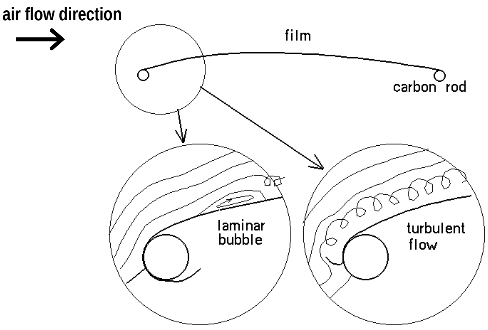

Figure 4: *Lightweight airfoil*

Computational models are promising, and may be of great help for the optimization of airfoils, which take care of the construction constraints. However, simple 2D airflow simulation programs (some of them are freely available on the internet) are not adapted for low *Re* numbers.

4. Propeller Design

The theory for a propeller [15] gives the following similitude laws, which are easy to develop from a simplified model (Figure 5):

Thrust	$T \propto Sv^2 \propto L^2\,(NL)^2 \propto N^2L^4$	(12)
Torque	$M \propto Sv^2L \propto N^2L^5$	(13)
Power	$P \propto Sv^2LN \propto N^3L^5$	(14)
Reynolds number	$Re \propto vL \propto NL^2$	(15)

N is the rotation speed (e.g. in RPM), and L a reference dimension, e.g. the center of the blade.

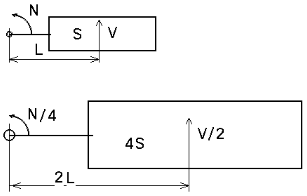

Figure 5: *Propeller model*

We are interested in getting a given thrust, and the challenge is to find the optimal blade dimensions. If $T \propto N^2L^4$ is constant, then $N \propto 1/L^2$. Hence,

Power	$P \propto N^3L^5 \propto 1/L$	(16)
Reynolds number	$Re \propto NL^2 = \text{constant}$	(17)

As a result, a twice larger propeller (figure 5) will spin at a quarter speed and require half the power. There is no aerodynamic change due to the *Re* number, but the larger propeller cannot be built with the same technology (it would be too heavy, since the weight ∝ L^3) and the aerodynamic parameters may change.

The theoretical shape for a propeller of a given pitch is easy to understand (figure 6). The pitch depends on the propeller's rotation speed and the plane's air speed. However, the air is pushed by the propeller at a speed that is difficult to know. We have plotted that speed for a steady plane (figure 6). The optimal angle of incidence for every section is hence difficult to define.

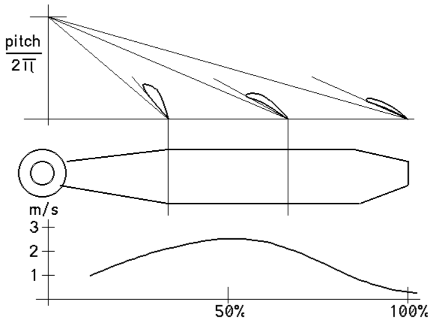

Figure 6: *Propeller design and generated air-flow*

Building balsa propellers is quite easy; testing them on a static bench with a balance gives a good idea of their quality at 1-2m/s. Data are available from our web site [20]. Preliminary results (figure 7) show that "good-looking" propellers of the same diameter have quite similar performances; their weight is related to their stiffness and maximum thrust. Commercial models are appropriate for 100-200g model planes but too heavy for ultra-light indoor slow flyers.

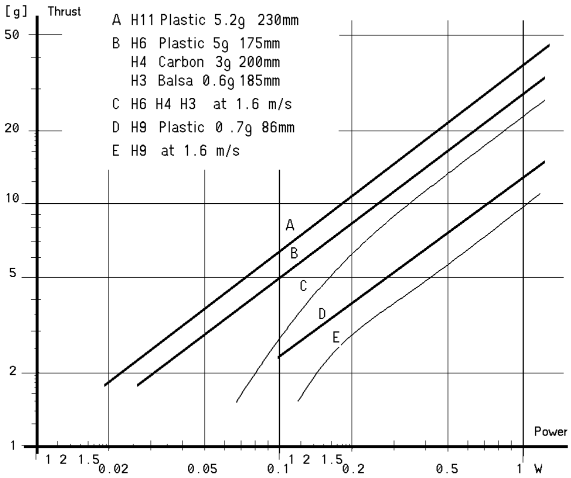

Figure 7: *Propeller comparison*

Notice that with relative air speed (measurements in wind tunnel), the thrust decreases at low torques. It even becomes negative when the torque is zero: the propeller is rotated by the wind - and has a higher drag than a blocked propeller.

Not surprisingly, the slope of the propellers lines is 2/3, as predicted by equations (12) and (14).

5. Motor Selection

Brushless motors are the lightest and the most efficient, but they need bulky command electronics. Therefore the use of coreless DC motors is almost inevitable. Those are available from a diameter of 4mm as low (pager motors) or high quality motors. These motors have a quite linear characteristic (figure 8).

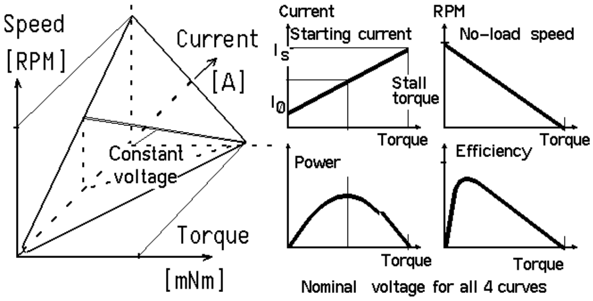

Figure 8: *DC motor characteristics*

The torque is proportional to the current I (torque constant k), and the rotation speed induces an electromotive force (EMF) that reduces the consumed current.

For a given motor, the power depends on the voltage, and significant over-voltage is possible if heat is well dissipated. Lifetime will be inversely proportional to the power. The coil resistance R dissipates power, and the power to weight efficiency depends on the magnet force, the coil volume and the air gaps.

$$\text{Torque} \qquad M = kI \tag{18}$$

$$\text{Electrical power} \qquad P_{el} = UI \tag{19}$$

$$\text{Mech. power} \qquad P_{mec} = \omega M = 2\pi(N/60)kI \tag{20}$$

$$= P_{el} - \text{losses} = UI - RI^2 - \text{friction losses} \tag{21}$$

U and I are the voltage and current supplying the motor. ω is the rotation speed [s^{-1}] and I_0 the no-load current. Note that the ratio between I_s, the stall current, and I_0 gives a good idea of the quality of the motor.

Maximum power is obtained at half the maximum torque, with half the maximum current:

$$P_{el,max} = UI_{max} = UU/(2R) = U^2/(2R) \tag{22}$$

$$P_{mec,max} = U^2/(2R) - RI_{max}^{\;2}$$

$$= U^2/(2R) - R[U/(2R)-I_0]^2 \approx U^2/(4R) \tag{23}$$

Adding a gear will increase the torque and reduce the output rotation speed, allowing better match with the propeller, as shown in figure 9.

Associated with the motor curves are current values that will define the battery size. Associated with the propeller curves are thrust values. A minimum thrust of about one third of the airplane's total weight is required for horizontal flight. Matching an existing propeller to a motor for which the reduction factor can be selected is hence possible. Reduction gears of different ratios are available for 4 to 10mm motors [20].

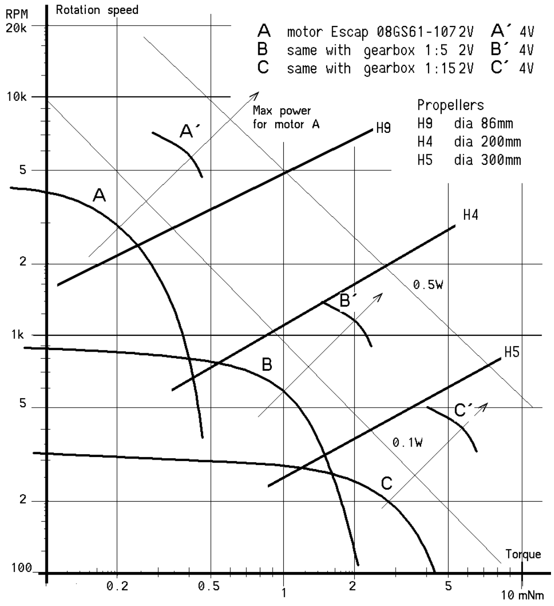

Figure 9: *Motor and propeller power*

6. Weight Budget

The problem with indoor flying is the weight of the batteries, reaching easily one third of the overall weight of the plane. Battery choices are limited for a model weighing less than 50g. The smallest NiMH (1/3AAA format from GP, 1.2V, 70mAh) weighs 2.4g per cell and has an internal resistance of 50mΩ. This means that a 4-cells pack will deliver only 500mA at 4V, one third of the battery power being dissipated within the battery itself. Lithium-Ion batteries (e.g., Renata, 330mAh, 10.1g) seem to be a good solution for improved endurance but require a step-up converter since their nominal output voltage is only 3.7V. Additionally, great care must be taken for the charging procedure. More recently, Lithium-Polymer batteries (e.g., 3.7V, 135mAh, 3.5g) have appeared on the market. They are quite lightweight since no hard package is needed.

Servos are also rather heavy. As a reference, the WES 2.4g servo has a force of 150g, and a current consumption of 100mA (which both are too high for our purposes). Magnets-in-a-coil servos are lighter but have a considerably reduced force. For savings of at least one servo and increasing maneuverability, a twin-motor plane is a solution to be tested. Motor speed control costs only a 0.1g transistor, but two motors instead of one is not the best for efficiency.

Off-the-shelf radio control receivers are available to as light as 2.3g. Infrared controls represent another unidirectional communication possibility for indoor flights, which weighs a bit less. We are currently investigated a digital bidirectional radio solution. The first prototype weighs about 4g, included a microcontroller for onboard control, a speed controller, and a step-up DC-DC converter.

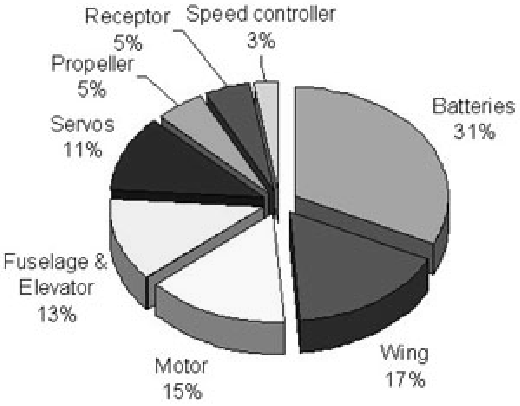

Figure 10: *Weight budget for the 50g C4 model plane*

Considerable care must be taken to reduce the weight everywhere. For the C4 plane, the weight budget is given in figure 10, and shows that half of the weight is in the batteries, servos and radio accessories.

7. Sensors, Navigation and Control

In addition to the weight budget of figure 10, a robot needs autonomous navigation components, which correspond at present to rather bulky electronics on "standard" mobile robots. Miniature electronic components and microcontrollers are quite easily available, but sensors are usually encapsulated without consideration of the weight. A one dimensional range finder may be useable for altitude control, but it is unconceivable to mount a sufficient number of distance sensors for general obstacle avoidance.

Inspiration should rather be taken from insects. For example, flies have compound eyes with very coarse resolution that indeed enable them to efficiently navigate through cluttered environments. Hence, it must be possible to obtain an obstacle avoidance behavior by using basic vision sensors [21-22] with few pixels or photoreceptors, and thus a low power requirement.

8. Conclusion

In this paper, we analyzed the different key components of a laboratory fixed-wing flying robot, namely its aerodynamics (wing), and its propulsion system (DC motor, gear, and propeller). We found that (i) aerodynamics at low Reynolds number is critical but still good enough for our purposes, (ii) some simple building techniques exist, which allow for realizing such a plane, (iii) there is a theoretical way to optimize the motor/gear/voltage/propeller set.

In order to demonstrate in real-life the conclusions of this analysis, a remote controlled model [18] has been developed, which is able to fly as slow as 1.4m/s (without payload). It weighs 47g and can easily maneuver in a 10x10m room. It uses an original solution in order to improve maneuverability at low speed - the direction is controlled by rotating the thrust system (motor, reduction gear, and propeller) around a vertical axis. This allows for tight turns with a radius of about 2m.

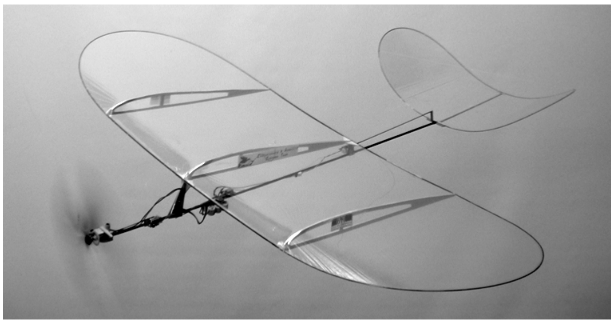

Figure 11: *Model C4*

Hopefully this work will contribute to the expansion of the indoor flying robot research field. Actually, we believe it is an appropriate and attractive test-bed for the development of bio-inspired robot controllers.

Acknowledgements

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