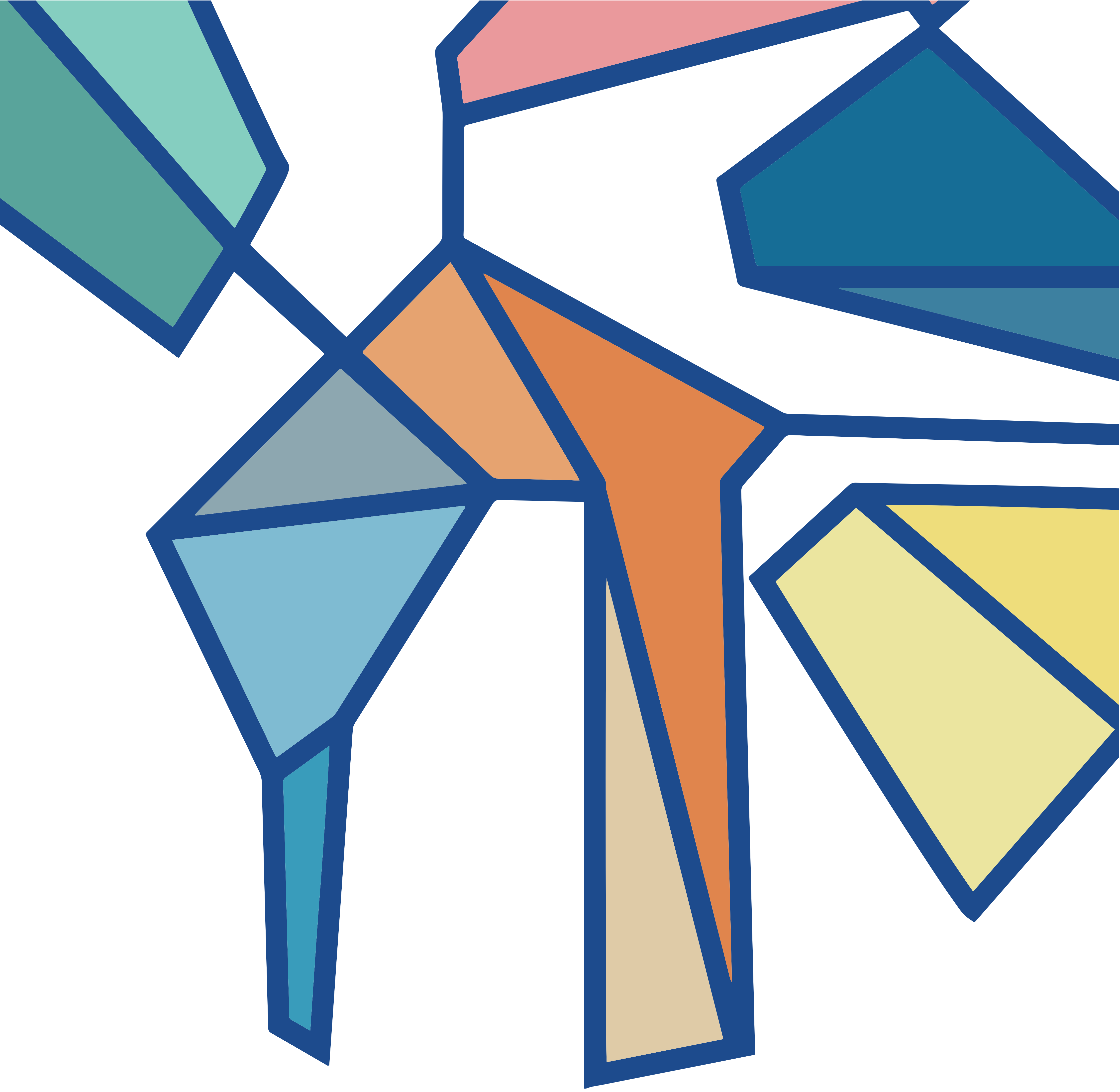

TEEM '15

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Design and Implementation of a Biologically Inspired Flying Robot

An EPS@ISEP 2014 Spring Project

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ABSTRACT

The goal of this EPS@ISEP project proposed in the Spring of 2014 was to develop a flapping wing flying robot. The project was embraced by a multinational team composed of four students from different countries and fields of study. The team designed and implemented a robot inspired by a biplane design, constructed from lightweight materials and battery powered. The prototype, called MyBird, was built with a 250 € budget, reuse existing materials as well as low cost solutions. Although the team's initial idea was to build a light radio controlled robot, time limitations along with setbacks involving the required electrical components led to a light but not radio controlled prototype. The team, from the experience gathered, made a number of future improvement suggestions, namely, the addition of radio control and a camera and the adoption of articulated monoplane design instead of the current biplane design for the wings.

Categories and Subject Descriptors

• **Social and professional topics~Model curricula** • **Hardware~Electromechanical systems** • *Social and professional topics~Sustainability* • *Social and professional topics~Project and people management* • *Social and professional topics~Codes of ethics*

Keywords

Biomimetic locomotion, educational toy, propulsion mechanism, flying robot

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1. INTRODUCTION

One line of research and development in robotics that has received increased attention in recent years is the development of biologically inspired robots. Whether robots use legs, wings or fins as a means to implement locomotion, the idea is to acquire knowledge of biological beings, whose evolution took place over millions of years, and apply the knowledge thus acquired to implement the same methods of locomotion (or, at least, use the biological inspiration) on the machines we develop. It is believed that, in this way, we are able to develop machines with capabilities similar to those of biological beings in terms of locomotion capacity and energy efficiency [1].

Upon the first EPS@ISEP presentation meeting, the students were organized into teams, according to the results of the Belbin Test, and were presented with several project proposals from which this team chose the bio-inspired flying robot [2].

The team was composed of four students, with different nationalities and backgrounds. Iain was a mechanical engineer student (therefore was responsible for the mechanical and electrical aspects of the prototype), Bénédicte a product designer student and was in charge the design, advertisement, logo and brand marking, Yvonne was studying sales and marketing engineering (was in charge of the project marketing planning and management) and, finally, Rauno, a student of materials engineering had the responsibility for the materials choice for the project.

According to the students, "*this project appealed to us because it would be challenging, yet possible. Furthermore we found it to be a very interesting topic since none of us had any experience with robotics but all are interested in the field of mechanics. Besides our interest in robotics, we liked the bio-inspired aspect of the proposal, since nature creates the most elegant and intelligent solutions to its problems.*"

The project proposal specified that the goal was to create a functioning ornithopter inspired by bird or insect like locomotion with a budget of 250 €. In particular, the robot should be able to take off, fly and land safely without any kind of propeller. The wings should flap based on the movements of the chosen bird or insect. Furthermore, the requirements specified the reuse of provided components, the selection of low cost hardware solutions, the usage of open source and freeware software, the strict adoption of the International System of Units (NIST International Guide for the use of the International System of Units) and the compliance with the Machines Directive (MD), Low Voltage Directive (LVD) and Restriction of the use of certain Hazardous Substances (RoHS) Directive. Additionally, the team was expected to find a market niche, identify a purpose and build the prototype of the intended product.

These specifications raised several questions: What kind of similar products are on the market already? What can the team create in 15 weeks and with a budget of only 250 €? How should the wings motion really work? How frequently do the wings have to flap? To what extent does the weight affect flight?

In terms of market positioning, the team decided that MyBird was going to be a toy for children. The proposed design, which is detailed in the product development section, is similar to a number of existing ornithopters. It uses four wings in two biplane pairs to generate lift and thrust and is powered by a lithium polymer battery. This approach requires the design and construction of the wings and body, a frame, a motor, a rechargeable battery and a set of complementary electrical components, which are listed in Table 1.

Prior to the ultimate functional test (whether or not the ornithopter actually flies), several tests, which are less likely to cause damage, could be carried out such as: (*i*) use load cells to ascertain if the wings produce enough force to support the weight of the ornithopter; (*ii*) use a wind tunnel to determine if it is able to manoeuvre once in the air as well as the maximum wind speed it endures; and (*iii*) measure the maximum distance it flies.

Although the paper is focussed on the technical aspects of the design and implementation of MyBird, the team also addressed other aspects concerning their project, namely the marketing plan, the eco-efficiency measures for sustainability to be considered during the development, the ethical and deontological concerns related to the product development and lifecycle and project management [2].

Bearing these ideas in mind, this paper is structured into five sections, namely: (*i*) Introduction, covering the presentation of the problem, the motivation for its choice and development and the objectives to be achieved, (*ii*) Related Work which describes the state of the art, covering existing technologies, (*iii*) System Architecture detailing how the project was envisioned and the prototype developed, (*iv*) Product Development presenting information pertaining to each aspect of the prototype such as materials, capacities and use, and, finally, (*v*) Conclusions and Future Developments on which the team reflects on the accomplishments and the possibilities for the future.

2. RELATED WORK

This section outlines five related systems found in the literature or commercially available.

2.1 Ornithopters

A lot of great minds have tried to build bird like wings on a human sized scale (Figure 1). Most models use a propeller for staying in the air, and many others just enable the human to float for a while. The bird wing movement, which is very complex, creates an equal combination of forces, being therefore not easy to copy [3].

Figure 1. Human wings developed by Lilienthal.

In recent years there has been a great deal of research into ornithopters and a surge of scientific papers, including prototypes similar to the one in this proposal. There are a number of identical systems commercially available offered as toys for children. The systems, which most closely resemble MyBird, are the Phoenix E-Bird and the Flytech Dragonfly. There are alternative designs described in other scientific sources, but their complex and expensive nature, dissuaded the team from trying to replicate or get inspired from any of these designs.

One of the first products researched was the E-bird (Figure 2). It is a toy currently on sale at around 26 €. The flight time is 8 min with a range of approximately 18 m. It is radio controlled and claims to mimic "a life-like flapping wing motion". Notable problems include the short flight time. The lack of information about this system may conceal other potential problems. It weighs just 14 g and charges in 8 min. It cannot take-off from a stationary position, meaning that it must be manually launched, and, once in the air, it can both dive and climb. Landing is basically a controlled, slow fall [4].

Figure 2. Phoenix E-Bird.

The Flytech dragonfly is similar to the E-Bird in terms of wing design (Figure 3). It is a toy aimed for children currently on sale and, although not available in Europe, it costs around 43 € and weighs 28.35 g. The body is made of Expanded Polypropylene, the wings are in mylar and the supporting rods and the internal structure is made of Delrin and Carbon Fibre [5, 6].

Figure 3. Flytech Dragonfly.

The Butterfly-type Ornithopter (BTO) is the result of a research conducted by graduate students from the University of Tokyo and, consequently, there is a great deal of information available. The entire system weighs just 0.4 g and includes no electronic components. BTO (Figure 4) relies upon low wing loading (ratio of wing weight to area) to function. This makes flight slow but gives a high range of mobility meaning that the wing size would have to increase dramatically if electrical components are to be incorporated. The system makes use of just one pair of wings acting in unison powered by an elastic band that gives it a flight time of just over 3 s [7].

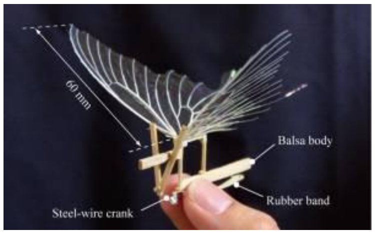

Figure 4. Butterfly-type Ornithopter.

The Micromechanical Flying Insect (MFI) was developed at Harvard University's School of Engineering and Applied Sciences (Figure 5). It is a truly tiny robot weighing just 60 mg. The wingspan is 3 cm and the wings have the highest strength to weight ratio of any aerofoil in existence; this includes biological aerofoils in addition to man-made ones. The MFI has very little control and the wings are connected to guide wires for stability and altitude control, however, there is no interference from friction between these wires and the insect [8].

Figure 5. Micromechanical Flying Insect.

The Del-Fly ornithopter was developed by Delft University (Figure 6). This ornithopter weighs just 15 g, is powered by a lithium polymer battery and can be remote controlled. There are, however, discrepancies in the report regarding the total cost of the project as traveling expenses and living costs are factored in as part of the final cost [9].

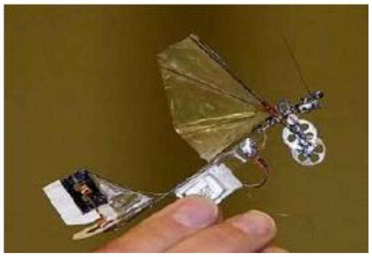

Figure 6. Del-Fly ornithopter.

2.2 Birds flight study

After analysing the reviewed systems, the first step was to choose between a bird or insect inspired model. The decision was to build a bird-like robot since birds, in general, have slower wing movements than insects. In addition, bird models are easier to study and build, as most insects have flexible and complicated wing structures. The following step was to compare the different types of bird wings and choose one.

The general wing dynamics [10] have a few components to consider. Since MyBird will only fly forward, the dynamics analysis becomes easier. The lift is produced by the airflow on the wing, which creates an aerofoil. The air pressure above the wing is lower than under the wing and this lift enables the bird to stay in the air. When the bird rotates its wings into the direction of the airflow, it can glide with the resultant angle. The thrust is produced by the flapping of the wings, which creates a circulation that is added to the existing lift. The two stages of flapping are the down-stroke, which provides the thrust, and the upstroke, which overcomes the drag. The drag consists of weight, friction, frontal form and lift-induced drag (Figure 7).

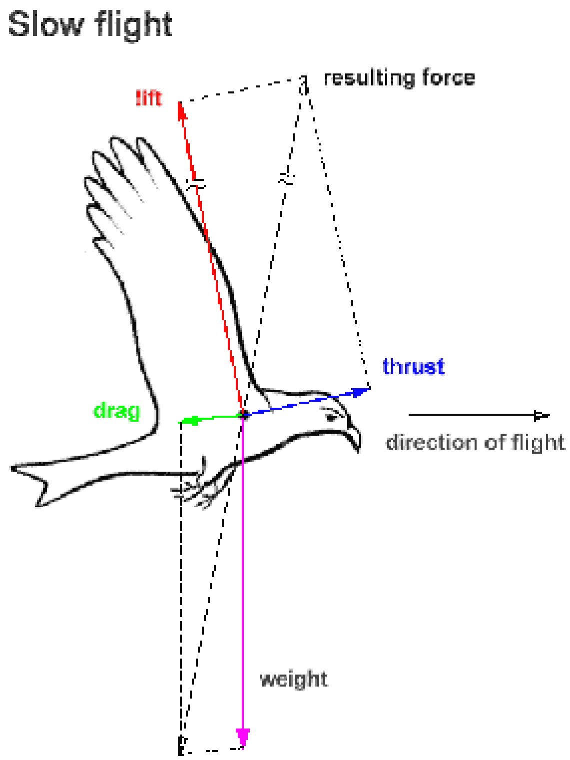

Figure 7. Forces involved in birds flight.

There are 4 different types of wings [11]: elliptical, high speed, high aspect ratio and soaring wings. Elliptical wings are designed to maneuver in spaces with a lot of obstacles. Examples of birds that have this type of wings are crows, ravens, blackbirds, sparrows and thrushes such as the American Robin. High speed wings are short and pointed to create rapid wing beats. Examples of birds that have this wing type are swifts, ducks, falcons, terns and sandpipers. High aspect ratio wings are far longer than wide and are used for slower flight, low energy consuming, and gliding. Examples of birds with this wing type include eagles, most hawks and storks. Soaring wings, which are typical of large birds, have curved tips to use the airflow optimally during flight. However, they need a longer taxi (runway on the ground before launching) to get up in the air. Examples of birds with this wing type are albatrosses, gulls and gannets.

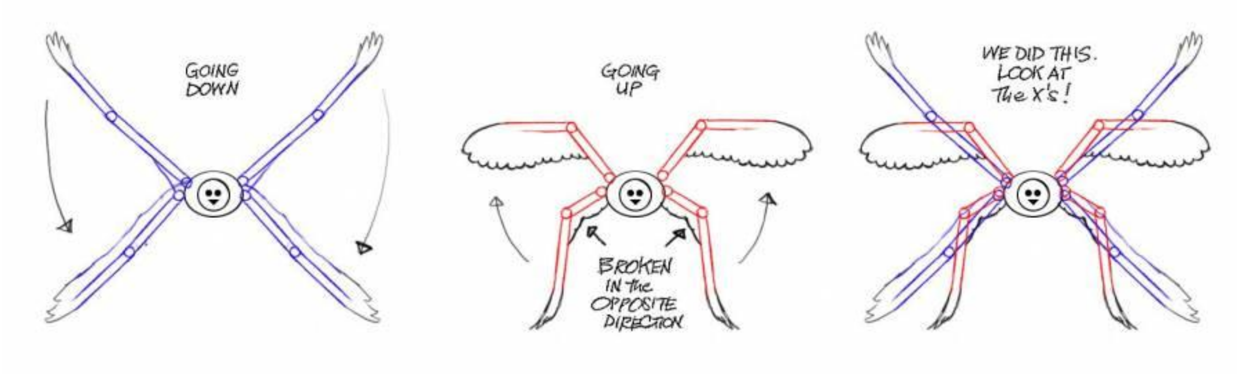

Figure 8. Planned wing beat of the ornithopter.

3. MYBIRD ARCHITECTURE

The dove is the source of inspiration for the MyBird design due to its size, colour and popular image, fitting perfectly into the children's toy picture. Therefore, MyBird was modelled as a white dove (Figure 8). In terms of fight, doves make a semi-folding movement of the wings that enables them to fly upward. The dove dimensions are suitable for the ergonomic limitations of a toy and compatible with the available budget. According to the defined marketing plan, the white colour is intended to give children the opportunity to customise their own flying bird with crayons or paint.

A number of different solutions on how to make the bird fly were researched and analysed. The following two designs depicted in Figure 9 illustrate the two final candidates. The monoplane in the right image of Figure 9 is more sophisticated (the wings bend) and mimics the actual flying movements. This monoplane design has articulated wings, which makes the movement more efficient. The flapping frequency can be kept lower (around 4 flap/s ~ 6 flap/s), resulting in higher energy efficiency. It also looks more realistic when it flies. However, the biggest problem with this approach was how to implement it, namely how should the wings bend? For this reason, this design was abandoned in favour of the biplane design, more typical of the insects, in particular the dragonfly.

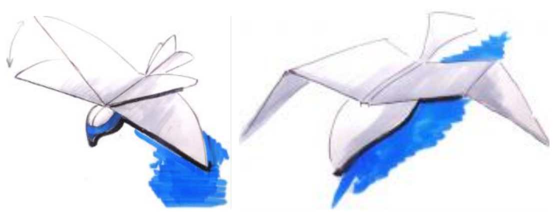

Figure 9. Conceptual drawings of the ornithopter biplane and monoplane design.

Therefore, in terms of wing design, the decision was to adopt the biplane wings (Figure 9, left), while keeping the monoplane with articulated wings (Figure 9, right) in reserve. In the event that MyBird is incapable of flying, the second design will be further investigated (as described in section 8). The adopted design comprises four wings in a biplane design (Figure 9, left). The wings will beat approximately 300 times per minute, one beat comprises of each separate biplane meeting in the middle, moving in opposite directions up and down before meeting back on the horizontal axis. To achieve this goal, a dedicated gear system must be designed and constructed (Figure 10).

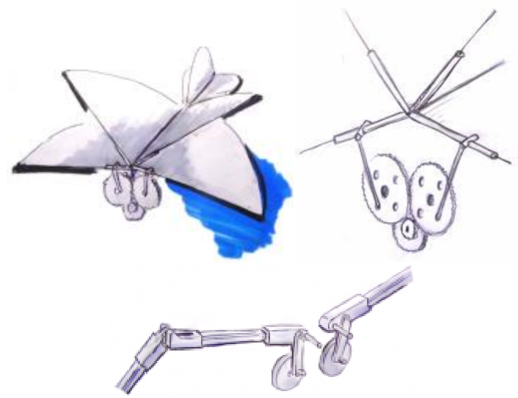

Figure 10. Conceptual drawings of the gear system.

In terms of dimensions, the decision was to create a body with a length of 30 cm and a width of 7 cm at its widest point, a wingspan of 50 cm and a weight close to 100 g.

Ornithopters require power to fly. A typical power source is a battery or fuel powered motor. In order to make a mylar-winged ornithopter fly, a motor requires around 100 W/kg of power. Alternatively, small ornithopters can be powered by rubber bands. This is the easiest type of ornithopter to design and build. The rubber band powers the entire power system, acting as both motor and battery. The rubber band is twisted to produce potential energy. When the rubber band is released, the potential energy is converted to kinetic energy and the torque produced makes the gears move and the wings flap.

Radio-controlled toys such as cars, helicopters and ornithopters are typically powered by an electric motor and battery. A general rule applies: as the length of the wing increases, the motor can rotate slower, but with a higher torque. This means that ornithopters with small wingspans require high speed motors.

4. MYBIRD DEVELOPMENT

The design of the prototype, which was done using Solid Works, is depicted in Figures 11-14. Lift is the force generated by propellers and wings to propel aircrafts and keep them in the air. Although lift is most commonly associated with the wing of a fixed-wing aircraft, it can be observed in the animal world as well. In this case, lift will be opposing gravity (weight). However, when an aircraft is ascending, descending or banking in a turn, the lift is tilted with respect to the vertical [12].

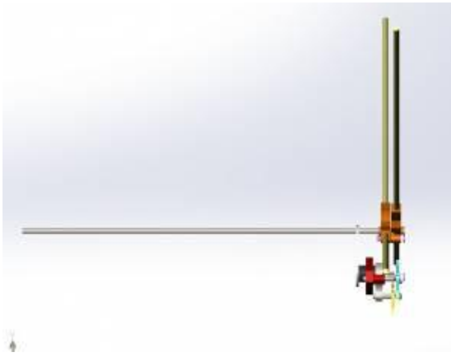

Figure 11. Prototype design in Solid Works.

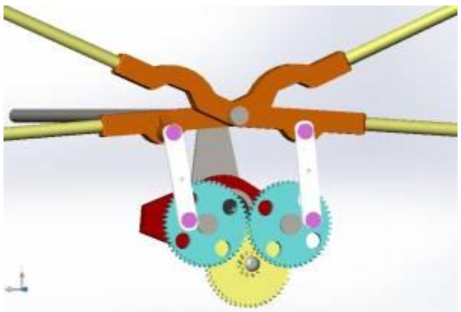

Figure 12. Detail of the gear system designed in Solid Works.

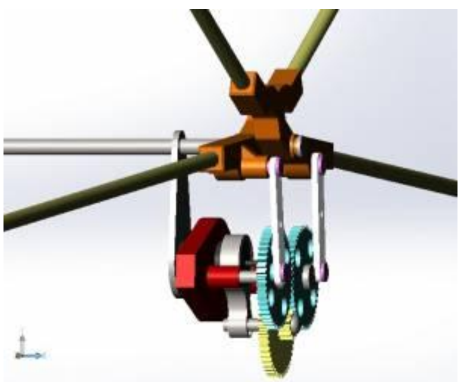

Figure 13. Detail of the wing actuation system designed in Solid Works.

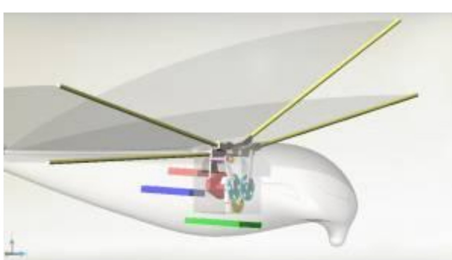

Figure 14. Complete prototype assembly in Solid Works.

MyBird is intended to fly at a velocity of around 5 m/s, which is safe for children operation and maintains the bird on the air. To calculate the lift, an aerofoil (shape of a wing) with a shape and thickness identical to the selected wing design and an appropriate Reynolds number must be used. In this case, the selected aerofoil was the E193, from the Eppler aerofoils, since it has a low Reynolds number (Figure 15) compatible with the intended type of low velocity flight.

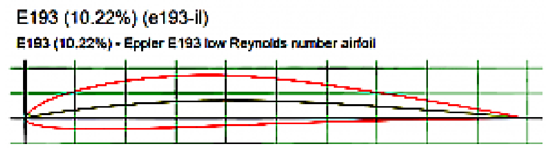

Figure 15. Eppler E193 aerofoil.

The lift coefficient was obtained from the specific aerofoil graph presented in Figure 16.

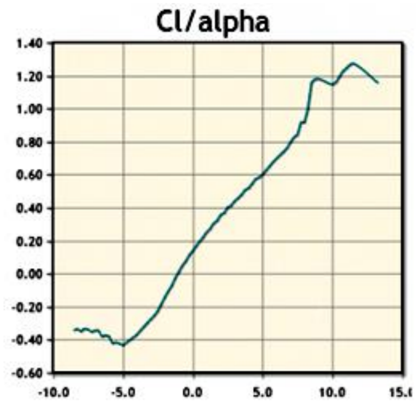

Figure 16. Chart of the lift coefficient *vs.* angle of attack.

Different calculations with several coefficients were performed since the weight of the ornithopter can vary. In the event that it will be slightly heavier than expected, the angle of attack (the angle between the body's reference line and the oncoming flow, the graph's *x*-axis) has to increase as will the lift coefficient [12]. Equation 1 determines the lift force developed by the wing, being F_L the lift force, e the density of the air (kg/m^3), A the cross-sectional area of wings (m^2), v the velocity (m/s), and C_L the lift coefficient (a dimensionless factor).

$$F_L = \frac{eAv^2C_L}{2} \quad (1)$$

$$F_L = \frac{1.23 \times 0.056 \times 25 \times 0.2}{2} = 0.172 \text{ N} \quad (2)$$

$$F_L = \frac{1.23 \times 0.056 \times 25 \times 0.4}{2} = 0.344 \text{ N} \quad (3)$$

Drag, also known as air resistance (Figure 17), is a type of friction that refers to forces acting opposite to the relative motion of any moving object.

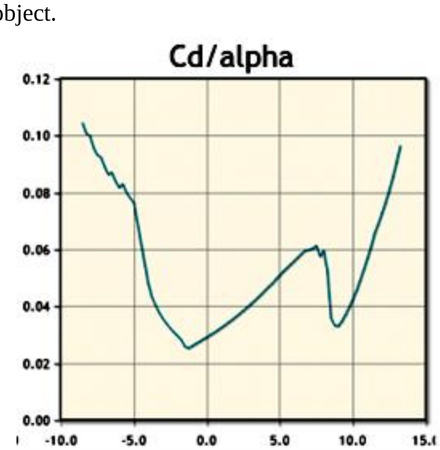

Figure 17. Chart of the drag coefficient *vs.* angle of attack.

The drag equation requires the selection of the drag coefficient, which is identical to the selection of the lift coefficient. The *x*-axis represents the angle of attack. If the aircraft is heavier, a bigger angle of attack and drag coefficient must be used [12]. Equation 4 presents the drag force developed by the wing (F_D), being e the density of the air (kg/m^3), A the cross-sectional area of wings (m^2), v the velocity (m/s), and C_D the drag coefficient (a dimensionless factor).

$$F_D = \frac{eAv^2C_D}{2} \quad (4)$$

$$F_D = \frac{1.23 \times 0.056 \times 25 \times 0.02}{2} = 0.0172 \text{ N} \quad (5)$$

$$F_D = \frac{1.23 \times 0.056 \times 25 \times 0.04}{2} = 0.0344 \text{ N} \quad (6)$$

From the drag force and the flying velocity it is possible to determine the minimum required power (Equation 7). However, this simplistic approach can only be used as a theoretical reference. Real motion is never as efficient as the theoretical results suggest and the bird will never fly with just the minimal required power. The chosen motor provides a power of 4 W of power, *i.e.*, a safety factor of 20 was applied.

$$Pot^{min} = F_D\, v \quad (7)$$

$$Pot^{min} = 0.0172 \times 5 = 0.086 \text{ W} \quad (8)$$

$$Pot^{min} = 0.0334 \times 5 = 0.172 \text{ W} \quad (9)$$

5. MYBIRD COMPONENTS AND IMPLEMENTATION

Once the design was defined, and the flight related forces and the minimum required power determined, it was time to work on the list of materials. The selection of the components was based on the project requirements. Different types of batteries, gear motors, remote controlling technologies and light and durable materials were considered and compared to choose the best solutions. Finally, when the materials arrived, the work in the workshop began.

5.1 Components

The selected motor is a 3.7 V brushless inrunner. Compared to outrunner motors, inrunners tend to spin exceptionally fast, often as high as 11 000 r/min/V. However, inrunners lack torque. As a result, most inrunners are used with a gearbox in both surface and aircraft models to reduce speed and increase torque. In this case the brushless coreless motor makes most sense since it is cheap, light and still energy efficient. Since the body is easy to take apart, it is also easy to replace the motor [13]. The chosen motor already has a 10:1 gear reduction and the output shaft is spinning at approximately 2000 r/min at 4 V. The MyBird design requires further gear reduction. To obtain the desired rotating speed of the final gears, the final stage has a gear reduction of 3:1. In this setup, if it rotates at around 660 r/min, the flapping frequency will be 11 flap/s.

The Arduino Pro Mini 328 3.3 V / 8 MHz, which is the smallest Arduino on the market, was chosen to control the motor together with a motor driver (1 A Dual TB6612FNG), to boost the output current.

The battery was chosen according to the most determinant factors: weight, capacity and discharge rate. A lithium polymer battery was selected, the ZIPPY 138 mAh 20 C Single Cell. This type of battery is commonly used in children's toys, is relatively safe, has a comparatively high energy density and is lightweight, which is a very important attribute for a flying object.

For the body, polystyrene was chosen because it is lightweight, has shock absorbing properties and can be easily shaped without any specific tools or skills. The material selected for the wings was Mylar because of its low density and great mechanical properties. For the leading edges and connection rods the recommendation is to use carbon fibre rods.

Table 1 presents the detailed list of material used in the prototype and the prices / unit from reference suppliers.

Table 1. Detailed material list to build the ornithopter

Name	Description	Quantity	Price / unit (€)
Electronics			
Motor	Brushless inrunner, 3.7 V	1	14.95
Microcontroller	Arduino Pro Mini 328 - 3.3 V/8 MHz	1	8.95
Motor driver	Motor Driver 1 A Dual TB6612FNG	1	7.75
Battery	ZIPPY 138 mAh 20C Single Cell	1	1.44
Body			
Polysterene	Floor insulation board M 125x60x4 cm	1	5.85
Wings			
Mylar	4 × A4 sheets	1	4.86
Leading edges / wing spurs	2 mm carbon fibre rods	2	1.75
Hinges	Designed and manufactured in the workshop	---	---
Driving mechanism			
Gearbox		2	6.0
Connection rods	Designed and manufactured in the workshop	---	---
Total cost of components			**59.30**

5.2 Electrical circuit

Since the Arduino's maximum output power is 150 mA and the motor requires around 1 A, the current driver was connected to the circuit. The complete electrical circuit of MyBird is presented in Figure 18, where Bat1 is the battery, U1 the Arduino, U2 the motor driver and M1 the brushed inrunner motor.

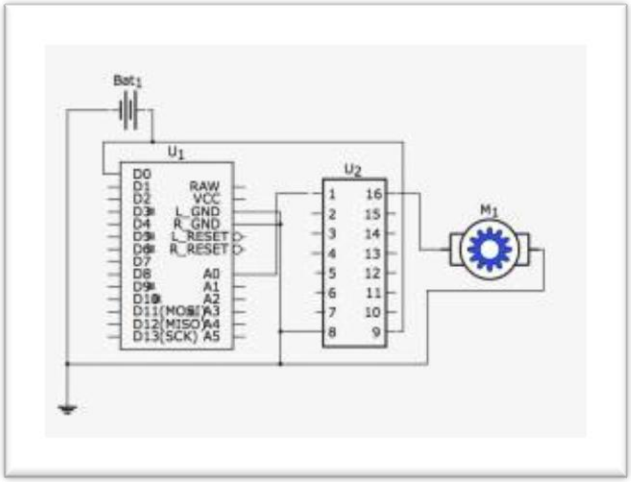

Figure 18. Electrical circuit schematic.

5.3 Functionalities

MyBird was designed as a flapping wing toy. However, if a camera is attached (further information about this option is in Section 8), it can be used for several different purposes, *e.g.*, it can be used by ornithologists to study birds. MyBird looks more natural than any similar "flying cameras" and it could be easily used to "go undercover" among birds. Additionally, it can be used to film events. At the moment drones (mostly quadrotors) are usually doing it, and they do get a lot of attention from the visitors. Furthermore, this type of ornithopter can also be used for advertising if a small flag with a logo or slogan is attached. When compared with drones, MyBird is lightweight (safer for the audience) and has a more natural and ecological design.

Although the original plan was to build a radio controlled prototype, this was not accomplished in this first version. The main implemented functionality is the ability to fly, *i.e.*, it should be able to fly for 5 min. This version does not include any direction and velocity control nor ensures that it will not crash prior to running out of power.

6. EXPERIMENTAL TESTS AND RESULTS

Figure 19 depicts a detailed view of the ornithopter wings actuation system. It is visible in this photo the motor that propels the wings and the gear system that works as the transmission system.

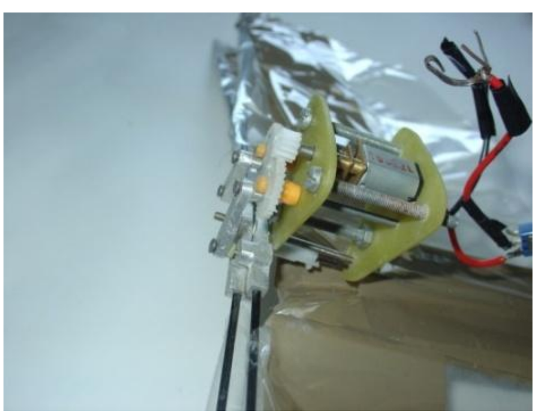

Figure 19. Detail of the prototype wings actuation system.

The assembled ornithopter is depicted in Figure 20.

Figure 20. Fully assembled prototype.

After the assembly of MyBird, tests were performed to check its ability to fly. The first tests involved checking the actuation system, to verify if the motor rotation would lead to the desired wing flapping. In the sequel, it was verified if the prototype could fly in an autonomous manner. In these tests the prototype was launched by hand, giving it an initial thrust, and it was concluded that although it flapped its wings, it was only able to fly for short distances of 3 m to 4 m and, subsequently, landed without control. This means that the initial goal of building a full flying controllable ornithopther was not achieved.

7. CONCLUSIONS

The project suffered a number of setbacks. According to the students, "*These failings are mostly our own fault since we should have ordered things sooner, made certain decisions earlier and been more organized in general. We are confident that these issues could have been avoided. We have, however, learned a lot from this project and we can draw conclusions from our experiences. Most ornithopters fly using a biplane system, the prevalence of this design suggests that this is the easiest method of ornithopter flight. Although any designs for monoplane ornithopters are extremely costly, according to the performed state of the art survey.*"

The initial plan was to design a flying object that mimicked, as closely as possible, the flight of a bird. However, the articulated wings proved to be too difficult for the team to design and, so, it was decided to adopt an already existing approach. The monoplane in Figure 21 is a more sophisticated and accurate design when compared to the flying movement of birds. This design has articulated wings, which makes the movement more efficient since the flapping frequency can be kept lower (around 4 flap/s to 6 flap/s). It also looks more realistic when it flies. The biggest problem for the team was how to implement this solution, particularly, how to make the wings bend.

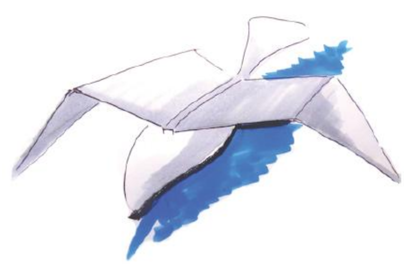

Figure 21. Concept of an ornithopter with articulated wings.

8. FUTURE DEVELOPMENTS

The most important future development is to control MyBird. Currently, there is no control whatsoever of the velocity, altitude or direction of the robot. Additionally, in order to control the direction, *i.e.*, turn left and right, it is necessary to place a rudder in the tail together with an actuator, *e.g.*, a servo motor. The radio control should be done either using standard toy operation frequencies (27 MHz or 49 MHz) or, preferably, standard Wi-Fi frequencies (2.4 GHz or 5 GHz) because they are more secure and are less prone to interference. The remote control must be powered by batteries that will also be used to charge the bird, with automatic charging taking place as soon as both are connected.

The initial plan contemplated the inclusion of a camera. However, since video recording is easily affected by any shaking or instability, a number of tests must be performed to ensure smooth flight. Weight distribution, wing shape, flapping frequency and type of wings are just examples of factors that can alter drastically the flight.

Finally, the articulated wings presented in Figure 21 must be fully designed, built and tested. This would be a serious evolution since there are no toys or ornithopters on the market with such wing design. Also, an ornithopter with articulated wings looks as real as a living bird and is more efficient in terms of energy since the resulting flap movement will make the bird fly with less energy.

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