

Numerical-experimental project of a radio controlled aircraft

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Abstract—The present work presents a remotely controlled aircraft design methodology. Differently from the common bibliography, that leaves experimentation to the last stages of design, this process is based on experimental data belonging to the aircraft configuration desired even in preliminary design stages. This increases the quality of numerical analysis at the same time that reduces its computational cost. Allying these factors, it is possible to design new configurations uncovered by bibliography or optimize an already established configuration to obtain great performance in specific missions.

Keywords — design, aircraft, radio controlled, UAV

List of Symbols

α	- Aircraft attack angle.
μ	- Aircraft friction coefficient with the ground.
ρ	- Air density
AR	- Wing aspect ratio.
bh	- Wingspan of the elevator.
bw	- Wingspan of the wing.
CD0	- Parasite drag coefficient of the aircraft.
ch	- Elevator Chord.
$C_{M\alpha}$	- Derivative of aircraft moment coefficient with the angle of attack.
C_{M_0}	- Aircraft coefficient of moment in cruise angle of attack.
CL	- Aircraft lift coefficient.
CL0	- Aircraft lift coefficient in take-off run.
CLMAX	- Maximum lift coefficient of the aircraft.
d	- Distance travelled by the aircraft.
D	- Drag force acting on aircraft.
e0	- Oswald efficiency number of the complete aircraft.
Fat	- Force generated by the rolling friction.
H	- Distance from the leading edge of the horizontal stabilizer to the leading edge of the wing.
k	- Spring constant.
L	- Lifting force acting on the aircraft.
MTOW	- Maximum takeoff weight.
N	- Normal force acting on the aircraft.
Sw	- Wing area.
T	- Powertrain thrust.
t	- Time.
VTO	- Take-off speed.
Vx	- Speed in the x direction.
W	- weight strength of the aircraft.
x	- Spring displacement.
XCG	- Center of gravity in relation to the leading edge of the wing.

I. Introduction

Aircraft design is usually divided into three parts: conceptual design, preliminary design and detailed design [4]. This is because the cost of building an aircraft is extremely high, so there is a great need for preliminary low-accuracy calculations to start the project, and then it is necessary to refine the calculations with powerful computational tools and wind tunnel tests for prototype validation before the aircraft can actually be produced and tested for certifications.

However, small aircraft such as UAVs usually have low production costs, and it is possible to construct an even cheaper prototype to acquire some data needed for the project. When harvested experimentally, these data generate the ability to obtain a more accurate preliminary design, increasing the ability to optimize the project of the radio controlled aircraft. Furthermore, even if a prototype is not built, the experimental apparatus needed to measure important variables like engine traction, and forces involved is much simpler and cheaper than that used for a full-scale aircraft.

In this context, according to [3], it is notable that fixed-pitch propellers are widely used in various types of aircraft. However, once this type of propellers aimed to UAVs and aircraft models have low efficiency as a function of the rate of advance, $\eta \leq 60\%$, it becomes very important to select a propeller that provides the best performance for the powertrain, since a significant part of the power available on the motor shaft is not used, getting lost.

Just like the performance of the powertrain, the rolling friction of an aircraft is a parameter that significantly influences its performance in ground operation, being a very important factor in the design and project of the aircraft throughout its landing and takeoff. A good prediction of the friction generated in the landing gear assemblage ensures good prediction of landing and takeoff distance, for example.

Conciliating the acquisition of experimental data in the conceptual or preliminary design stages, the accuracy of the computational model adopted is improved with a low computational cost. With this precision it is possible to carry out design of different configurations not yet explored in the literature, as well as to optimize already existing configurations for a specific mission. Thus, it is intended to demonstrate with this work the importance of a faithful numerical model to predict the performance of an aircraft with experimental parameters. With such fidelity, it will be shown how an optimization can present extremely significant gains for a mission, as the load capacity of the aircraft.

II. Methodology

Given the challenges presented, obtaining experimental values to start the project is important for its development. Within these parameters it is worth mentioning the available traction generated by the powertrain to be used, as well as landing gear roll friction values. Once VANTS and radiocontrolled aircraft are generally smaller than full-scale aircrafts, obtaining these data is relatively simple because of the ease equipment handling when compared to manned aircraft. In addition, they may add greater fidelity to the numerical model when compared to theoretical values available in literature.

The experimental values, along with other project criteria, can be coupled in a numerical analysis to evaluate the performance of the aircraft in its flight mission observing parameters such as lift, drag, maximum takeoff weight and distance, maximum speed and stall speed. This analysis allows the classification and selection of the best aircraft that present satisfactory configurations for the proposed mission.

Then, using the analysis method for the proposed mission, it will be necessary the application of an optimization method to evaluate and select the best aircraft configuration within a previously defined group in order to obtain a plane with better performance for the mission.

Firstly, the mission of the aircraft needs to be defined. For this, it will be designed in order to achieve the best air cargo performance within a takeoff distance limit. More specifically, the aim is an aircraft with the maximum MTOW able to operate in 60 m of runway, subject to some dimensional regulations on the wingspan and longitudinal length of the aircraft, which sum should not exceed 3.5 m.

The engine available for the development of the project was the O.S. 0.61FX, being necessary the selection of the best propeller available in the inventory for such engine. The propellers available are APC Propellers brand, in dimensions 13x4W, 13x6, 12.25x3.75SF. These sizes are recommended by the motorization manufacturer. The method of such evaluation and selection is the comparison of the results obtained in statics and dynamics thrust tests, evaluated in wind tunnel.

Since the configuration, geometry and positioning of the landing gear of the aircraft was already set, by parameters that will not be treated in this work, it is possible to define the coefficient of friction for the set of tricycle landing gear. For this, a sequence of dynamic tests is applied based on a concept of conservation of energy.

By combining the values obtained experimentally, as well as some design values, it is possible to define the best empennage geometry (wing, horizontal and vertical stabilizer) for the powertrain by using the developed takeoff analysis coupled to an optimization by the method of Differential Evolution.

The obtained results are compared evaluating the constructive feasibility and cost, choosing the best aircraft that brings a good performance, without detriment in the productive sector involving both the constructability and the available budget.

A. Thrust test

In order to obtain the motor thrust with the available propellers, a test bench equipped with a PW6D HMB load cell with 10 kg of load capacity associated to a data acquisition set from the software DASyLab 11. The test bench was positioned in front of a wind tunnel for speed variation. The maximum thrust values provided by the powertrain for each of velocities of 0, 5, 10, 15 and 20 m/s are used to determine the maximum thrust curve as a function of the wind speed available in its flight conditions. The Fig. 1 shows the experimental apparatus already placed in the test configuration in wind tunnel.

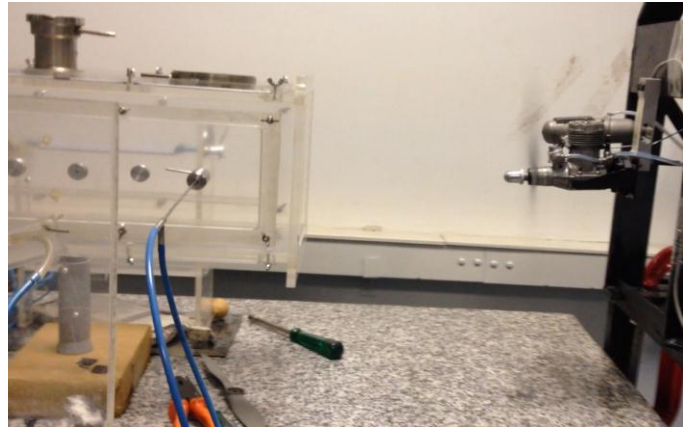


Figure 1. Experimental assembly used for the thrust test.

In order to reduce the influence of the sequence in which each propeller is evaluated, the same regulation of the engine and the same type of fuel were maintained throughout all the thrust tests, being the fuel a mixture of methanol with a proportion of 10% of nitromethane and 18% oil. Furthermore, between each propeller change, a complete cooling of the engine was awaited before a new test.

B. Friction Test

With the thrust parameters of the powertrain collected and evaluated, the experimental part focused on the determination of the coefficient of friction of the landing gear set. For this, based on the concept of conservation of energy, it is possible to relate known forms of energy with the energy dissipated by the movement along a surface with determined friction. Equation (1) demonstrates the equality between a known elastic potential energy source and the energy dissipated due to friction over a known distance, where k is the elastic spring constant, x is a compression applied to spring, N the normal force, μ the coefficient of friction of the set and d the travelled distance.

$$\frac{kx^2}{2} = N\mu d \quad (1)$$

A model of the landing gear set with a similar layout to that one previously defined was built, with a capacity of load variation close to the proposal of takeoff weight of the aircraft in design. By using an apparatus with a known elastic constant spring installed on a support constructed for the purpose of

compressing, locking and releasing the spring, it was possible to do launches of the prototype model on an asphalt surface close to the one in which the operation of the aircraft will operate.

After several model launches, modifying the mass load configuration and the distance measurements for each launch, a linear regression plot of the inverse of the distance travelled by the prototype versus the load divided by the elastic potential energy was obtained. Thus, the coefficient found for such a graph is numerically equal to the coefficient of friction. The Fig. 2 and the Fig. 3 demonstrates the methodology applied as well as the arrangement of the components at the beginning and at the end of the test respectively.



Figure 2. Example of the beginning of the friction test.



Figure 3. Example of the end of the friction test.

C. Aircraft Analysis

The aircraft's mission defines the analysis required for its flight. Thus, as the main requirement is the take-off within 60 m runway with the maximum MTOW, the mathematical

modelling of take-off was developed. In this way, the previously determined experimental parameters as well as the variable project parameters are considered in an ODE to predict the aircraft behavior in compliance with the proposed mission.

First, an aerodynamic analysis of the proposed geometry is made, taking into account its wingspan, wing area and aerodynamic profile. After this analysis, the drag coefficient values are used in the analysis of forces acting during takeoff and flight to verify the design requirements.

The takeoff analysis is based on Fig. 4, performing the balance of forces in the X and Y directions. With the available data of the experimental tests, the thrust curve obtained in the thrust test and the rolling coefficient of friction are used. The other coefficients are taken from the literature [4] and [6].

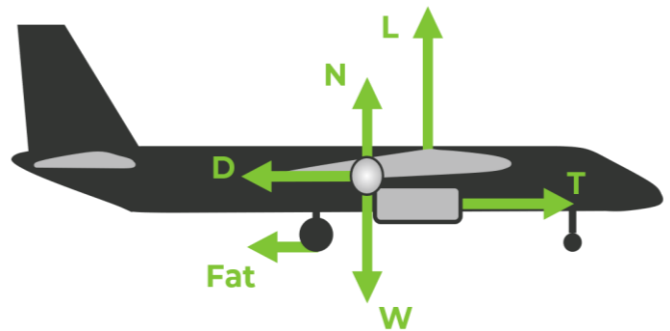


Figure 4. Balance of forces acting on the aircraft during takeoff.

The balance of forces is demonstrated (2), already in differential form for the use in numerical integration. The forces can be developed to better comprehension and determination of them. The thrust remains as a function of the horizontal velocity because its curve is obtained experimentally as described in the previous sections, and can therefore be a generic function.

$$\frac{dV_x}{dt} = T - D - F_{at} \quad (2)$$

Thus, by the development of the drag force by the drag coefficient, the drag force through the drag polar and the friction force by the coefficient of friction, as in the takeoff analysis present in [4], leads to (3).

$$\frac{dV_x}{dt} = \frac{T(V_x) - \frac{1}{2}\rho V_x^2 S_w \left(CD_0 + \frac{1}{\pi a_0 AR} C_{L_0}^2 \right) - \mu \left(mg - \frac{1}{2}\rho V_x^2 S_w C_{L_0} \right)}{m} \quad (3)$$

In order to obtain the velocity as a function of the position, the chain rule can be used as in (4) and perform the integration of the expression, replacing the thrust force by the function obtained by regression to the experimental data. Thus, velocity as a function of distance can be obtained by numerical integration, or by analytic integration of the expression, if possible.

$$\frac{dV_x}{dx} = \frac{1}{V_x} \frac{T(V_x) - \frac{1}{2}\rho V_x^2 S_w \left(CD_0 + \frac{1}{\pi a_0 AR} C_{L_0}^2 \right) - \mu \left(mg - \frac{1}{2}\rho V_x^2 S_w C_{L_0} \right)}{m} \quad (4)$$

The aircraft can take off if at the end of the prescribed distance its speed is higher than the takeoff speed, considered 20% above the stall speed, condition described in (5).

$$V_{TO} \geq 1.2 \sqrt{\frac{2mg}{\rho S W C_{LMAX}}} \quad (5)$$

Static longitudinal stability conditions are imposed on the aircraft to ensure flight of the aircraft, while the wing and the horizontal stabilizer can be dimensioned simultaneously, as well as their position relative to the center of gravity. For this, a nonlinear aerodynamic analysis based on Weissinger's theory is used, as presented in the work by [2]. With this method, the drag and lift coefficients of the empennages, as well as the induced angles of attack of the empennages, are predicted, which allows the interpolation of the 2D section airfoil used data, becoming a robust analysis with low computational cost. A longitudinal stability analysis method was coupled to the aerodynamic analysis [1], without the linearizations involved in the original. With this implementation is possible to predict the moment coefficient for the various aircraft angles of attack.

Thus, the aircraft is considered stable when its derivative of moment coefficient related to the angle of attack is negative at all points in the flight envelope, and less than a threshold based on aircraft of similar size. In addition, it needs to have the coefficient of positive moment in the angle of attack of cruise, trim condition of the aircraft. The stability conditions are shown in (6) and (7).

$$C_{M\alpha} < C_{M\alpha_{ref}} < 0 \quad (6)$$

$$C_{M0} > 0 \quad (7)$$

D. Optimization and Selection of Final Aircraft

Using the analysis methods presented until now, an optimization with geometric constraints and stability restrictions can be applied in order to maximize the load carried by the aircraft. For this, a Differential Evolution method is applied, presented by [5]. It is a stochastic method not based on derivative methods. An infographic demonstrating the optimization process is shown in Fig. 4. Each aircraft consists of a wing span vector, wing area, position of gravity center relative to the leading edge of the wing, distance from the leading edge of the horizontal stabilizer to the leading edge of the wing, stabilizer wingspan and also its chord as indicated in (8). This aircraft vector will be optimized by the process described in Fig. 5, with the main objective is the maximum MTOW.

$$\{\text{AIRCRAFT}\} = \{b_w, S_w, X_{CG}, H, b_h, c_h\} \quad (8)$$

At the end of the process, a record of all aircraft is created, ie all of process 1 and process 7 in Fig. 5 is obtained. The data

are analyzed to verify the aircraft that will be the most cost-effective in the mission, since the MTOW is the most important function but it is also necessary to judge the production cost and manufacturing. Thus, an aircraft considered the best by the designers is selected.

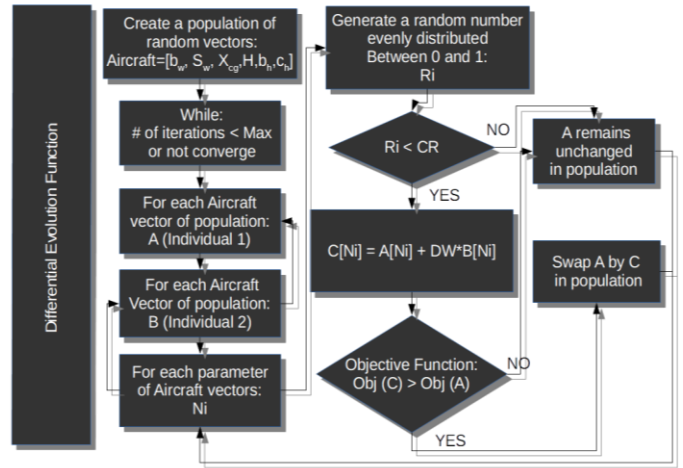


Figure 5. Explanatory infographic of the optimization process.

III. Results and Discussions

After the tests with all proposed propellers, the maximum thrust values were obtained for each of the propellers in each speed range evaluated, as shown in Table 1.

TABLE I. Maximum average thrust for respective speed ranges

Propellers and Speeds	0 m/s	5 m/s	10 m/s	15 m/s	20 m/s
12.25x3.75SF	45,95	44,93	43,73	42,52	40,50
13x4W	44,43	43,99	42,89	41,99	40,11
13x6	43,41	42,59	42,13	40,50	39,00

From these values, it was possible to obtain the maximum thrust curve of the propellers as a function of the wind speed, as shown in Fig. 6, enabling their evaluation and comparison.

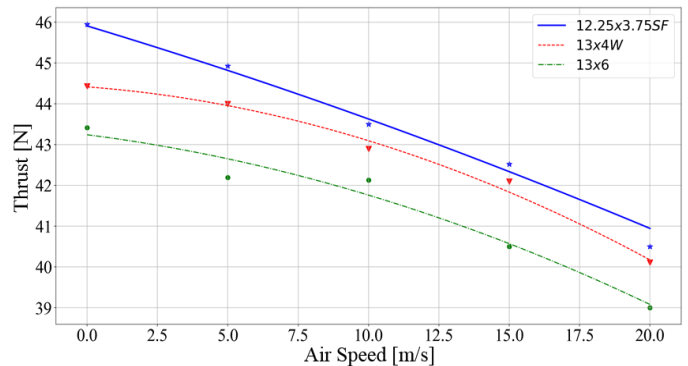


Figure 6. Maximum thrust as a function of wind speed.

With the evaluation of the results obtained, the propeller 12.25x3.75SF was chosen for use in the powertrain of the

aircraft. This showed a significantly higher thrust throughout the operating speed range when compared to the other two propellers tested, especially at low speeds, being this a condition of great importance for the development of better takeoff performance.

In the friction test, knowing the value of the elastic spring constant and its compression stroke, being 1086 N/m and 0.0506 m respectively, it was possible to determine the elastic potential energy involved in the landing gear test set, which was approximately 1.390 J.

After this, by carrying out the prototype tests with defined masses, noting the distance travelled in each shot, obtaining an average value for each normal force acting in the set. The mean values found are shown in Table 2.

TABLE II. Normal Force and the average travelled distance of each load configuration

Normal Force (N)	22,32	29,90	37,99	45,90	54,05
Distance (m)	1,385	1,157	0,847	0,742	0,637

From these values, it was possible to obtain the graph of the inverse of the distance travelled versus the normal force by Elastic Potential Energy. Since the coefficient of friction is numerically equal to the angular coefficient of the line obtained by the least squares method, a value approximately to 0.0382 was determined. The generated graph is shown as in Fig. 7.

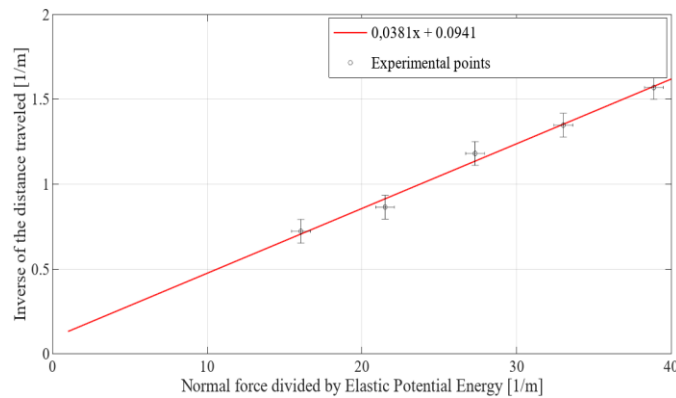


Figure 7. Maximum thrust as a function of wind speed.

The friction value and the best propeller 12.25x3.75SF regression curve were coupled to the analysis described in the Aircraft Analysis section. In this way, it was possible to start the optimization process as described in Fig. 5. In all, 7845 aircraft were evaluated during the process, which are shown in Fig. 8, Fig. 9, Fig. 10, Fig. 11. In the first two figures are present analyzes regarding the wing of the aircraft. It can be observed that the wingspan is a limiting factor, since the MTOW increases directly to the span. The wing area seems to have an optimal point for each wingspan, as show the agglomeration of points of the same size in Fig. 9.

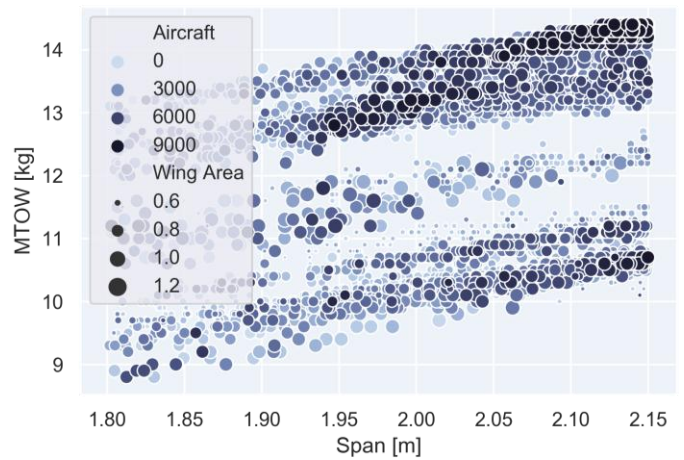


Figure 8. Evaluated aircrafts and convergence process showing the variables related to the wing.

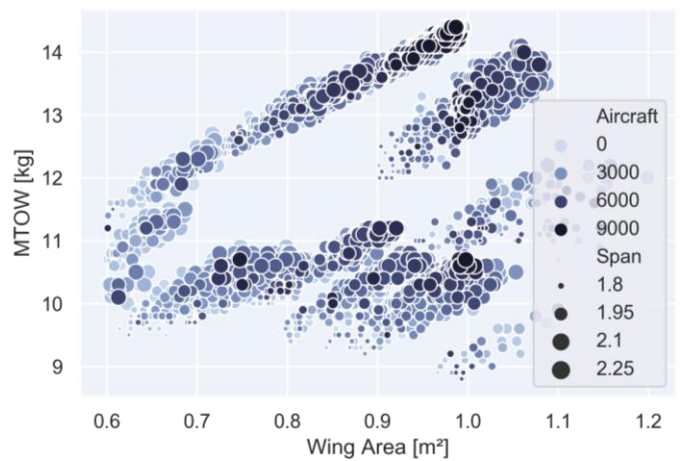


Figure 9. Evaluated aircrafts and convergence process showing the variables related to the wing.

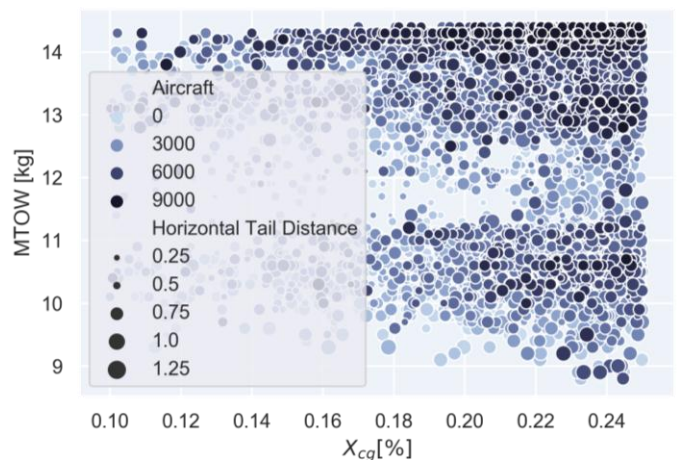


Figure 10. Evaluated aircrafts and convergence process showing the variables related to stability.

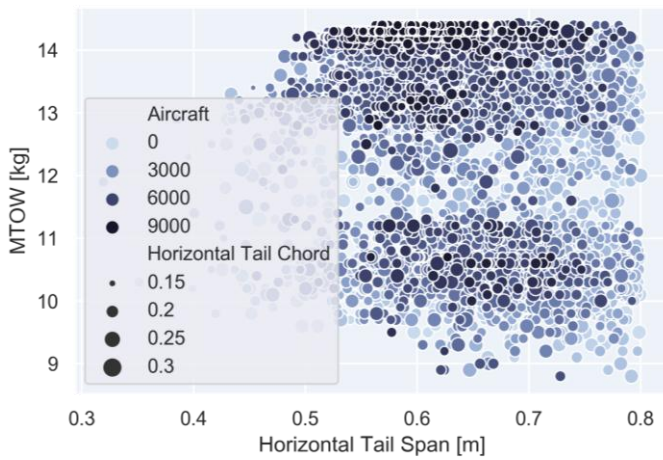


Figure 11. Evaluated aircrafts and convergence process showing the variables related to the elevator.

The Fig. 10 represents the aircraft from the point of view of stability. As can be observed, the stability does not strongly influence the performance of the aircraft, since there are individuals with MTOW close to the maximum obtained in all regions of the graph and with varying sizes. Thus, it is concluded that the CG position is hardly relevant, as well as the tail distance, serving both as constraints.

Something similar occurs with the elevator analysis shown in Fig. 11. With the exception of a small area to the left, the observed behavior in the previous graph repeats.

As it is a nonstructural analysis, the observed behavior for the wing span and the elevator span was already expected, since the maximization of these allows the reduction of aerodynamic drag and consequent increase of speed, which impacts on the MTOW of the aircraft. In this way, the coupling of a structural analysis could add great value to the optimization and demonstrate even more efficient and constructible aircraft. As there is no such analysis yet, the aircraft selection considering constructability and empty weight of the aircraft depends significantly on the experience of the designer, affecting the final result of the optimization.

The final dimensions of the chosen aircraft are shown in Table 3, having a MTOW of 14.40 kg.

TABLE III. Final dimensions of the selected aircraft

b_w [m]	S_w [m ²]	X_{CG} [%]	H [m]	b_h [m]	c_h [m]
2,140	0,9868	0,2386	0,740	0,580	0,194

IV. Conclusions

With the realization of the tests, as well as the evaluation of the results obtained from these, it was possible to select the best propeller available for the proposed engine to integrate the powertrain of the aircraft and to raise its maximum thrust curve for different operating speeds. It was also possible to estimate a real value for the rolling friction coefficient generated by the landing gear set, which is approximately equal to 0.0382.

The selected aircraft has dimensions totally constructible by manufacture. It is a small aircraft, that makes it

transportable. Its engine has only 550 g and less than two horsepower, but with this configuration it is capable of carrying 14.40 kg of full load. From a material point of view, it is an inexpensive aircraft because its wing area relatively small, once it is directly proportional to the cost. In addition, a rectangular configuration was chosen for empennage due to the simplicity of construction by manufacture which will be the method used for initial construction. This does not mean that the analysis and optimization used are limited to these characteristics.

The parameters of entry, thrust and friction were fundamental for the continuity of the initial design of the aircraft and consequently numerical optimization, since these are relevant to evaluation of the performance in ground and takeoff run. Numerical optimization made it possible to obtain an extremely efficient aircraft in terms of maximum takeoff weight. It can be observed that even with a large quantity of possibilities of project, a configuration capable of standing out to all others has been defined even considering all the imposed constraints.

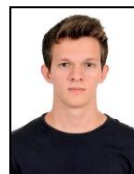
Acknowledgment (Heading 5)

The acknowledgments are for UNESP - São Paulo State University "Júlio de Mesquita Filho" and Ilha Solteira Engineering Faculty for material and financial support and the Zebra Team of SAE Brasil Aerodesign for technical support and collaboration with this work.

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