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Development of a multidisciplinary analysis tool for drone design

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Abstract

In the last decade, we have witnessed the boom in the production of drones, that are unmanned aircraft.
The exponential growth of the presence of drones in our skies is mainly due to their constant technological advancement and to the fact that their applications have increasingly diversified and are continuing to do so at an impressive rate.
Today drones no longer have only military or modeling purposes, but they have proved to be very useful, sometimes indispensable, in many other contexts, among these we find agriculture, public order, filmography, photography and recently they are developing drones for the delivery of goods.
Given the diversity of the fields of use of these aircraft, the loads to be transported, the flight times and the altitudes reached vary from application to application and from mission to mission.
The purpose of my Master's Thesis is to provide the designer with a tool to perform the exploration of the design space of a drone, given high-level requirements such as the payload mass and the flight autonomy. The tool helps the designer identifying the design solutions to fulfill the requirements in terms of system level architecture and subsystem level components.
To do this I have developed a MatLab tool which, knowing some mission parameters, such as payload and required autonomy, provides indications for the choice of batteries, motors, propellers and controllers to be used.

List of abbreviation

Abbreviation	Description
AIO	All-In-One
AIT/V	Assembly, Integration, Test and Verification
AOA	Angle Of Attack
AUW	All Up Weight
COTS	Commercial Off-The-Shelf
EPS	Electric Power System
ESC	Electronic Speed Controller
FC	Flight Controller
FPV	First Person View
GND	Ground
HD	High Definition
LED	Light-Emitting Diode
LiPo	Lithium Polymer
MBSE	Model-Based Systems Engineering
PDB	Power Distribution Board
PPM	Pulse-Position Modulation
ROS	Robot Operating System
RSE	Robotic Systems Engineering
RX	Radio Receiver
T/W	Thrust to Weight ratio
TX	Radio Transmitter
UART	Universal Asynchronous Receiver-Transmitter
VTX	Video Transmitter
WDR	Wide Dynamic Range

Table 1: List of abbreviation

Chapter 1

Introduction

1.1 Draft PoliTo

DRAFT PoliTo is a student team at Politecnico di Torino that researches and develops innovative solutions infused with Artificial Intelligence with the goal of increasing the autonomy of current drone technology.

The team is organized into five groups: *Robotic Systems Engineering*, *Deep Learning and Computer Vision*, *Obstacle Avoidance and Motion Planning*, *Simultaneous Localization* and *Mapping and Business & Outreach*.

The RSE group handles the analysis, design, fabrication, assembly, integration, and test of aeromechanic and avionics systems. Performs software DevOps and develops virtual environments for the integrated simulation of robotic systems.

A small subgroup of RSE has devised and developed a MatLab tool capable of helping the drone builder to choose the components to be used in order to carry out a specific mission. This tool is called TRIDENT.

1.2 TRIDENT

The RSE Tribe is developing TRIDENT, a tool for the comprehensive multidisciplinary design of rotorcrafts. The tool is meant to support feasibility and preliminary design phases by providing a user-friendly environment for a fast evaluation of initial guess of design to be optimized in detailed design phases.

TRIDENT exploits MBSE techniques to model systems, subsystems, and components and their mutual interactions with the aim to provide a single environment for the integrated system-level analysis of drones. The tool requires input parameters about performance and characteristics of several drone systems, including structure, motors, propellers, and battery.

Moreover, also the ROS model adopted for the simulation of the drone implements a lift and drag model that requires input parameters about the aerodynamic features of propellers. Information about the values of these parameters might be hard to retrieve, especially regarding the COTS components typically adopted for the fabrication of amateur drones. Therefore, these parameters must be measured in a standard fashion and dedicated test infrastructures and test procedures must be developed to achieve so.

The scope of this activity is to provide end-to-end development of test infrastructures (hereafter named testbeds), including:

- definition and management of testbed's requirements, functional analysis, trade studies, testbed's architecture definition, and interface requirements definition;
- analysis, design, fabrication and AIT/V of testbeds, including structures, mechanisms, EPS, control electronics, sensor's suite;
- development and integration of software infrastructure

for testbed control, data acquisition and processing, hardware/software integration, test and verification;

- definition of test procedures and methods;

- Selection of hardware/software items and support to their procurement as needed.

In 2020 the first version of the tool was completed. This first version was subject to substantial changes to solve some bugs and improve the general reliability of the code. In 2022 we released the version 2.0 which ensures excellent reliability of the results and great compliance to flight tests.

1.3 Problem explanation

DRAFT Polito takes part in competitions every year and works on projects that involve the construction of drones. Every competition and flight project has different requirements. The design process is iterative and the usual approach is to perform it by hand: starting from requirements some initial guesses about the sizing of the main components is made, then continuous refinements by hand are performed to converge toward the final solution. This process is long, laborious and usually prevents exploring the whole design space, thus limiting the design choice to significant suboptimal solutions. To solve this problem, an automated tool has been devised to speed up the process of exploring the full design space in order to save the designer's time and effort and to provide a full overview of all the potential solutions. This way, the designer can focus on optimizing the design choices according to the mission requirements.

This paragraph defines the main components of a drone and indicates the main characteristics that determine the design choices that the developed tool can make.

1.3.1 Multirotor Hardware

The first step to building a drone is to understand the components that it uses to fly.

Figure 1.1: Nyx drone photo

A multirotor consists of the following essential components:

- frame
- motors

- electronic speed controller
- propellers
- battery
- flight controller
- RC Receiver

If the drone fly FPV, it will also need the following elements:

- FPV Camera
- Video Transmitter
- FPV antenna

There are other non-essential but useful hardware for example buzzer, LED's, HD Camera, GPS etc [1].

Frame

The frame of a drone is the main structure, or the skeleton upon which the rest of components will be attached. Once it is decided on what the craft to do (Aerial Photography, Racing, Micro Freestyle etc.), the first thing to do is decide what size best suits the requirements.

The size and the plant of the frame will determine what size and the number of the propellers (or vice versa), in turn the size of the propellers will determine the size of the motors, which will specify the current rating of the ESC's.

PDB

PDB stands for Power Distribution Board and it is often where the battery power lead is connected. As its name suggests, the PDB distributes power to the components at the voltages they require. These days the necessity of using a PDB is being negated by FC's, ESC's and other (dubbed AIO) components providing the same function.

Flight Controller

The Flight Controller is the brain of a drone, it has sensors on the board so it can understand how the craft is moving. Using the data provided by these sensors, the FC uses algorithms to calculate how fast each motor should be spinning for the craft to behave as the pilot is instructing via stick inputs on the TX or as the autopilot is indicating.

Most of the wiring on the drone will be focused around the FC. It needs to have the RX connected, so it can be told what the pilot wants the craft to do. Each of the ESC signal and ground wires need to be connected for the FC commands to be carried out by the motors.

RX

Transmitters (TX) and receivers (RX) are not universal and an RX must be compatible with the TX. These days it is most likely using either PPM or a digital Serial protocol, which will only require one signal wire for all of the channels, plus power and GND.

Electronic Speed Controller

An ESC is a device that interprets signals from the flight controller and translates those signals into phased electrical pulses to determine the speed of a brushless motor. When selecting an ESC, the current rating must be higher than the amperage drawn by the combination of motors and props.

These days an ESC has 4 input terminals, 2 are for signals coming from the FC. Signal and signal ground are wired to the FC, the 2 heavier wires are for Positive and Negative, they carry the high current to the ESC to supply the motor. These Positive and negative are wired to the PDB. An ESC has 3 output terminals, one for each of the wires of a brushless motor. If the FC has an integrated PDB then all 4 wires going to the ESC input will come from the FC. 4-in-1 ESC's are becoming popular as they can shave a few grams off the AUW [2].

Motors

There are two types of motors used in RC, Brushless and Brushed motors. Generally it is used brushless motors on larger models (such as racing drones, and any bigger models), and Brushed on the micro drones and toy drones. This study will focus on brushless motors.

The motors are the main drain of battery power on the quadrotor, therefore getting an efficient combination of propeller and motor is very important.

Motor speed is rated in KV, that indicates how many revolutions per minute (rpm) that it turns when 1V is applied with no load (e.g. propeller) attached to that motor.

Generally, a lower KV motor will produce more torque and a higher KV will spin faster, higher KV motors also have shorter windings and thus lower resistance. It lowers maximum voltage rating and increases the current draw for the motor and propeller combo.

There are many aspects to motor performance aside from raw thrust, high among these is how much current the motor draws from the battery (the ESC's are rated to withstand the maximum amperage draw of the motors)[3].

Propellers

There are possibly thousands of different types of propeller for drone, with multiple options in almost every size. A heavier propeller will require more torque from the motor than a lighter prop, also blades with a higher AOA encounter more resistance from the air and require more torque. When a motor must work hard to turn, it draws more Amps. Finding a balance between the thrust produced and the amperage used by the propeller and motor combination is the most complicated choice to make to build a multirotor.

The propeller depends on the size of the motors and battery voltage, instead to pick the right pitch, shape and number of blades, really depends on what sort of flying style pilot plans to do.[5]

Battery

LiPo batteries are the most common power sources of the drones. LiPo is used because of the high energy density and high discharge rate.

LiPo batteries are rated by their nominal voltage ($3.7V$ per cell), cell count in series, (shown as a number followed by 'S') ie $4S = 14.8V$, capacity in mAh (ie.$1300mAh$) and discharge rate or C rating (ie. 75C).

Increasing the battery capacity might give longer flight time, but it will also get heavier in weight and larger in physical size and it can decrease the autonomy because the battery is the single heaviest component of the craft. There is a trade-off between capacity and weight, that affects flight time and agility of the aircraft. The figure(1.2) shows the relations between this parameters[6].

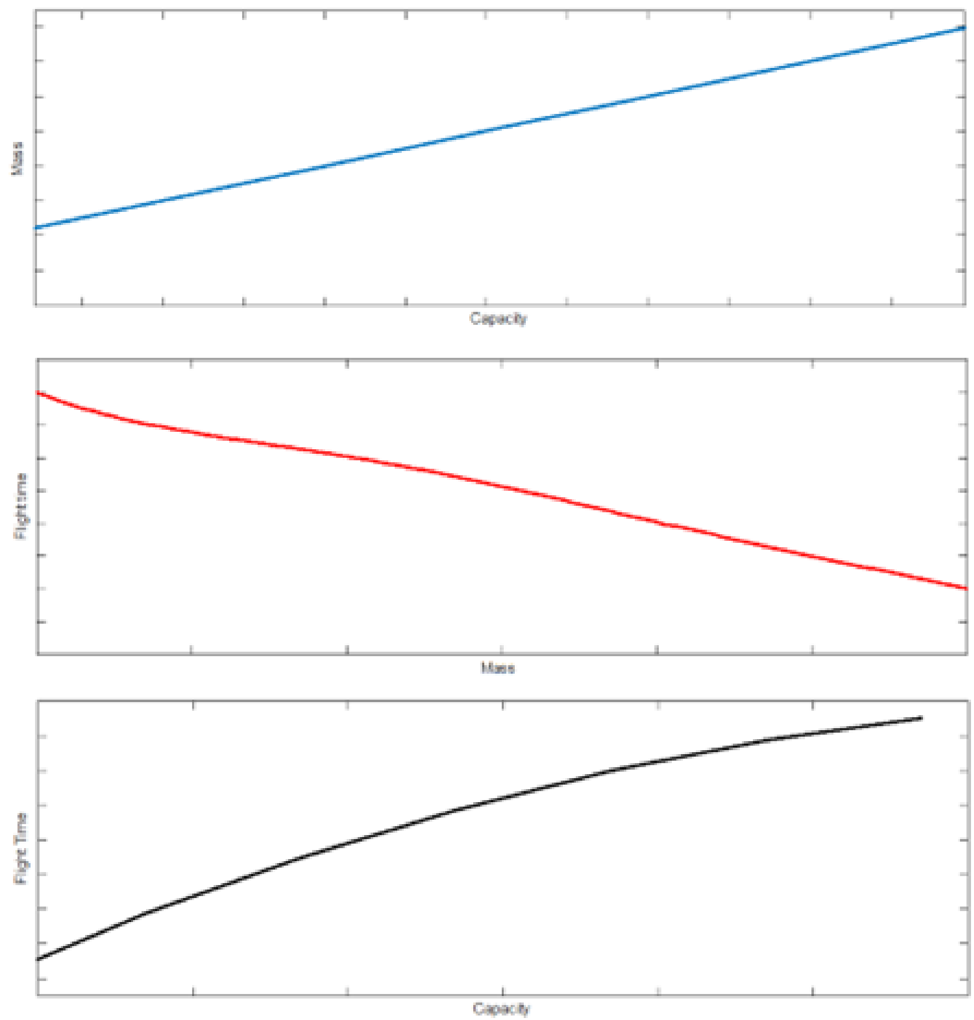

Figure 1.2: Relation between Autonomy, Capacity and Mass

Some batteries come with two C-ratings: "continuous" and "burst" ratings. The Burst rating is only applicable in short period of time (e.g. 10 seconds). If C rating is too low, the battery will have a hard time delivering the current to the motors, and the drone will be under powered[4].

FPV Camera

An FPV camera allows the pilot to see the view from onboard the craft. On an FPV mini drones, there are normally 2 cameras, one for real time video streaming, and the other for recording HD footage.

FPV cameras don't have great video quality – they are designed for WDR (Wide Dynamic Range) and low latency, which is extremely important to FPV. WDR refers to a camera's ability to display changes in lighting conditions, and areas of shadow and light in the same image. Latency is the amount of time between the FPV camera capturing the image and display that image on the screen or in the goggles.

Video Transmitter

Video transmitter, or VTX, connects to the FPV camera to transmit video to the FPV goggles or monitor.

The VTX will receive a signal from the FPV camera (often via the FC) which it then broadcasts.

FPV Antenna

Every VTX requires an Antenna to transmit signal. Antennas come in various shapes and sizes, directional, linear and polarized.

Optional Components

The most common additional components added to a mini drones are LED's and a lost model buzzer. These are really important for a beginner, especially if he don't have a nice flat area of mown grass, the drones can go really quickly which means it can be far away quite fast.

1.3.2 Choice of components

The drone components can be divided into two groups, the first consisting of those that are useful for satisfying the mission requirements relating to flight and its duration (propellers, motors, battery, ESC), the other group includes the components that meet the other objectives.

While for the second group the choice of what to include in the hardware project can be subjective or be dictated by the mission itself, the choice of the components of the second group is complicated given the interdependence of the elements.

There are some tools that can help in this choice. Draft PoliTo for the construction of drones relied on the tool *eCalc*.

eCalc *eCalc* is a tool that performs reliable simulations of electric drives. In particular, it can be used to check if a drone can fly and for how long before building it. In fact, by inserting the weight of the drone, the number of rotors and the model used of batteries, ESC, motor and propeller, some characteristics of the flight are obtained in output including autonomy in hovering, with the engine at maximum or with maximum efficiency. These outputs are essential in order to know if the drone built with certain characteristics can meet the mission requirements that are to be imposed.

Therefore, this tool can provide a great help in the construction of multirotors, but it implies a choice made in advance by the builder and cannot determine the optimal combination of the various components. From the need to solve these problems TRIDENT was born, the first tool able to make a unique choice of the components that guarantee the flight of the drone.

Chapter 2

Theoretical Background

TRIDENT is a tool that uses different physical models to perform the calculations necessary to determine the characteristics of the drone components.

In this chapter we will illustrate the physical-mathematical theories used to study the flight of the multirotor.

2.1 The Propulsion

The thrust that keeps the drone in flight is produced by propellers that rotate simultaneously around distinct axes, the number of propellers is chosen by the user. Neglecting the interference forces between the various propellers, the total thrust is assumed as the sum of the thrusts produced by each individual propeller.

To calculate the thrust produced by the propeller are used the formulas deriving from the theory of the blade element and the Rankine-Froude theory, which will be illustrated in this paragraph.

2.1.1 The Theory of the blade element

The Theory of the blade element provides a model that allows to calculate, in a sufficiently correct way, the aerodynamic forces and the moments acting on a rotating blade, through the approximation of the latter to a series of elements of infinitesimal thickness, oriented in the direction of the strings and aerodynamically independent.

This theory neglects the effects of the blade tip and the interactions between the various elements that make it up.

Basically, the Theory of the blade element assumes that each element behaves like a two-dimensional airfoil on which a pressure distribution is generated when it is hit by a flow with velocity v_e and incidence α.

The flow velocity is therefore the resultant of the induced velocity v_i and of the rotation speed ωR. The incidence α, on the other hand, is defined by the difference between the keying angle θ and the angle ϕ that is formed between the directions of ωR and v_e.Therefore, knowing the aerodynamic quantities, speeds and angles involved, it is possible to obtain the values of dL (lift) and dD (drag), which insist on the infinitesimal profile, and, subsequently, it is possible to obtain the values of dT (thrust), dC (torque) and dP (power), which, integrated on the whole blade, allow to calculate the macroscopic values of the propeller performances.

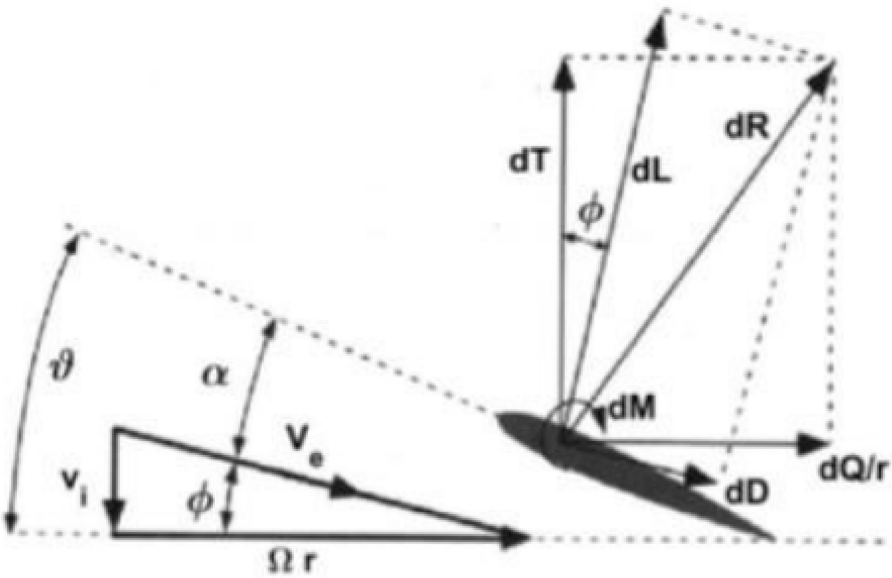

Figure 2.1: Theory of the blade element[7]

Mathematical formulation

Consider the blade element placed at a distance r from the rotation axis of the helix, of thickness dr, chord c inclined by a keying angle θ and hit by a flow with an effective speed v_e with an angle of incidence α e with an inflow angle ϕ. As already mentioned, v_e is the vector sum between the induced axial velocity v_i and the vector velocity r. The speed v_e results to be dependent in module and inclination ϕ to r.

$$\theta = \alpha + \phi \tag{2.1}$$

$$\phi = \arctan\left(\frac{v_i}{\omega R}\right) \tag{2.2}$$

$$|\vec{v_e}| = \sqrt{{v_i}^2 + (\omega R)^2} \tag{2.3}$$

With C_l, C_d and α_0 which are respectively the coefficient of lift, the coefficient of drag and the incidence of zero lift, we can define the forces dL and dD acting on the element:

$$dL = \frac{1}{2}\rho {v_e}^2 (r)\, C_l (r)\, dS = \frac{1}{2}\rho {v_e}^2 (r)\, C_l (r)\, c\, (r)\, dr \tag{2.4}$$

$$dD = \frac{1}{2}\rho {v_e}^2\left(r\right)C_d\left(r\right)dS = \frac{1}{2}\rho {v_e}^2\left(r\right)C_d\left(r\right)c\left(r\right)dr \tag{2.5}$$

In the calculation of the propeller performance, it is important to detect the thrust T and the torque Q, which are respectively the perpendicular component of the sum of the aerodynamic forces acting on the blade and the horizontal component multiplied by the arm r.

$$dT = dL\cos\phi - dD\sin\phi \tag{2.6}$$

$$T = \left(dL\sin\phi - dD\cos\phi\right)r \tag{2.7}$$

Assuming a very small inflow angle ϕ, the following approximations are valid:

- $\cos\phi \approx 1$
- $\sin\phi \approx \phi$
- $\phi \approx \frac{v_i}{\omega R}$
- $v_e = \omega R$

The thrust and the torque then become:

$$dT \approx dL = \frac{1}{2}\rho(\omega R)^2 C_l c dr \tag{2.8}$$

$$dQ \approx \left(dL\phi + dD\right) = \frac{1}{2}\rho\omega^2 R^3\left(C_l\phi + C_d\right)cdr \tag{2.9}$$

It is now possible to obtain the power necessary to move the blade element at speed v_e:

$$dP = \omega dQ = \frac{1}{2}\rho\left(\omega R\right)^3\left(C_l\phi + C_d\right)cdr \tag{2.10}$$

It will therefore be necessary to integrate over the entire radius and multiply by the number of blades N to obtain the overall values for the entire thrust propeller, torque and power:

$$T = \frac{N\omega^2\rho}{2}\int_0^R C_l c r^2 dr \tag{2.11}$$

$$Q = \frac{N\omega^2\rho}{2}\int_0^R (C_l\phi + C_d)\, cr^3 dr \tag{2.12}$$

$$Q = \frac{N\omega^3\rho}{2}\int_0^R (C_l\phi + C_d)\, cr^3 dr \tag{2.13}$$

It follows that for geometrically similar propellers, traction is proportional to the density of the air, to the square of the number of revolutions and to the fourth power of the diameter, while the torque is proportional to the density of the air, to the square of the number of revolutions and to the fifth power of the diameter, finally the power is proportional to the air density, to the cube of the number of revolutions and to the fifth power of the diameter. Renard's formulas derive from this analysis:

$$C_t = \frac{\pi^2}{4}\frac{T}{\rho\omega^2 R^4} \tag{2.14}$$

$$C_q = \frac{\pi^2}{4}\frac{Q}{\rho\omega^3 R^5} \tag{2.15}$$

$$C_p = \frac{\pi^2}{8}\frac{P}{\rho\omega^3 R^5} \tag{2.16}$$

At this point, the propeller efficiency can be calculated, determined by the ratio between the useful power TV and the power supplied by the power shaft. Defined the advancement ratio $J = \frac{V}{nD}$, where n are the rotations per second, it can be found that:

$$\eta = \frac{TV}{P} = \frac{C_t}{C_p}J \tag{2.17}$$

2.1.2 Rankine-Froude Theory

The Rankine-Froude Theory is based on the conservation laws of fluid dynamics to give an estimate of the performance of the propeller relative to the thrust produced and the induced speed generated, considering the flow that hits the rotor as stationary, irrotational, inviscid and incompressible, therefore governed by Euler's laws.

The rotor is replaced by a disk of infinitesimal thickness, called the helix disk, and near this the mass flow and axial speed is uniform, while the pressure is discontinuous due to the thrust generated by the propeller which also causes a speed variation.

Thrust T turns out to be:

$$T = \dot{m}\,(V_{+\infty} - V_{-\infty}) \tag{2.18}$$

Indicating with v_i the increase in speed to the disc and with w the increase at infinity, thrust results:

$$T = \rho A_d\,(V + v)\,[(V + w) - V] = \rho A_d\,(V + v_i)\,w \tag{2.19}$$

By equating this equation to the variation of kinetic energy over time, it can be shown that $w = 2v_i$. Substituting into (2.19) thrust turns out:

$$T = 2\rho A_d\,(V + v_i)\,v_i \tag{2.20}$$

In hovering, or stationary, as in the case studied, $V = 0$.

$$T = 2\rho A_d {v_i}^2 = 2\pi\rho {R_d}^2 {v_i}^2 \tag{2.21}$$

$$dT = 2\pi\rho {v_i}^2 r dr \tag{2.22}$$

From this formula it can be seen that the larger the rotor diameter, the lower the induced speed v_i needed, therefore the lower the induced power P_i.

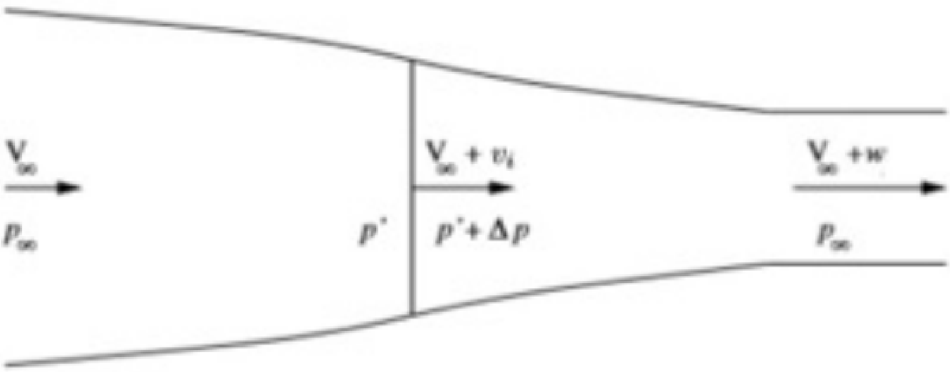

Figure 2.2: Rankine-Froude Theory [7]

2.1.3 Speed limitation

In order to avoid having any profile of the blade in supersonic regime or unpleasant effects due to the creation of shock waves, it is necessary to check the value of the maximum speed incident on the blade. This value, which must be well below the speed of sound, is equal to the speed at the tip of the blades, calculated as $V_{tip} = \omega R$, where ω is the rotation speed in rad/s and R is the radius of the propeller in m. The limit is arbitrarily M_{max} assumed to be $0.65 Mach$. Therefore, it is easily to get the maximum speed at tip and the maximum angular speed:

$$V_{tip_{max}} = VsM_{max} = 158.92 m/s \tag{2.23}$$

$$\omega_{max} = \frac{V_{tip_{max}}}{R} \tag{2.24}$$

2.2 The electric power system

The power needed to drive each propeller is provided by a dedicated motor that uses the energy stored in a LiPo battery.

The physical models used for EPS sizing are listed below.

2.2.1 The Motors

Electric motors are described by two parameters K_v and K_m, the first indicates the revolutions per minute performed by the motor per unit of voltage across the motor while the second indicates the torque generated by the motor per unit of current that passes through it.

Another fundamental parameter is the efficiency η of the motors, defined as the ratio between the mechanical power generated and the electrical power absorbed by the motor.

The electrical power absorbed is defined as the product of the voltage across the motor and the current that passes through it, the motor is considered in steady state and the various transients are neglected, consequently any reactive effects, that could occur due to the latter, can be neglected.

Furthermore, the mechanical power is defined as the product of the angular velocity and the torque to which the rotor is subjected.

From the previous considerations it follows that:

$$K_v K_m = \frac{\omega_{RPM}}{V} \frac{\tau}{I} = \frac{P_{mec}}{P_{el}} = \eta \tag{2.25}$$

It is easy now to found that:

$$K_v = \frac{60 \omega I c \eta}{2\pi P_{el}} \tag{2.26}$$

with c that is a limitation current factor.

2.2.2 The Electronic Speed Controller

For the dimensioning of the Electronic Speed Controller (ESC) to be connected to each motor, the tool found the nominal current, which is dimensioned through the application of the Joule effect.

$$P_{el} = R{I_{nom}}^2 \tag{2.27}$$

$$I_{nom} = \sqrt{\frac{P_{el}}{R}} \tag{2.28}$$

The power considered is the max power provided multiplied by a safety factor equal to 0.6.

2.2.3 The Battery

Most of drones use Lithium Polymer Batteries, known as LiPo, because they are rechargeable and because of their long run time and high power.

To choose the battery to use, it is necessary to calculate the required capacity and the discharge rate and it is possible only knowing how is the battery discharge curve.

Battery discharge curve are based on the potential that occurs during the discharge. The area under the discharge curve corresponds to the amount of energy that a battery can supply and it is strongly correlated to operating conditions. The graph in figure(2.3) shows as the potential drops during the discharge and it is related to:

- IR drop, that is the drop in cell voltage due to the current flowing across the battery's internal resistance;

- activation polarization, due to the retarding factors inherent to the kinetics of an electrochemical reaction;

- Concentration polarization, that considers the resistance faced by the mass transfer process by which ions are transported across the electrolyte from one electrode to another.

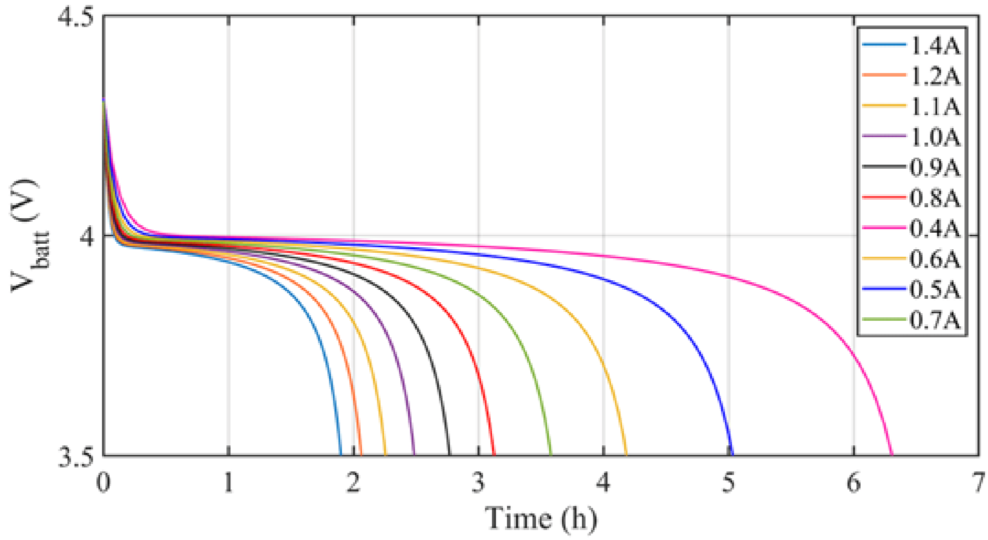

Figure 2.3: Relation between battery voltage and time [8]

The figure shows also how the battery discharge curve depends by the discharge current that can change a lot the time of flight. In last analysis, it is important to not complete the discharge cycle at the end of the discharge curve because that extremes conditions can damages the battery. So, it must be defined the depth of discharge DOD, which indicates how much the battery is discharged at each charge cycle.

The discharge curve central part is draw by this equation:

$$V_t - V_0 = -A \int_0^t I_{t'} dt' - RI_t \tag{2.29}$$

In this equation it is assumed that each cell of the battery has a constant internal resistance R.

Finally knowing the requested autonomy of flight, the battery voltage, amperage and DOD, it can be calculated the battery capacity and weight.

2.2.4 The electrical circuit

The electrical circuit of a classic drone can be schematized as shown in the figure(2.4):

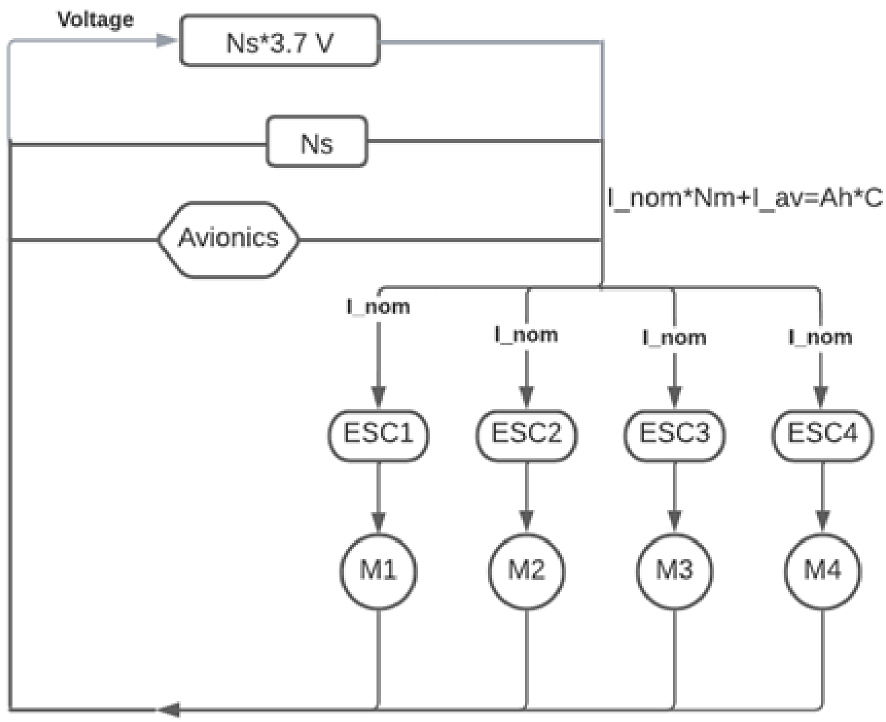

Figure 2.4: Electrical circuit of a classic drone

The battery cells are considered in series: the total voltage is given by the product of the unit voltage of a cell by the number of cells while the current delivered will be equal to that delivered by each cell.

The resulting current load, product of the battery capacity and charge rate, as can be seen, is given by the sum of current required by the motors (I_{nom} is the direct current dimensioned in the ESC block) and current required by the avionics system installed on the drone.

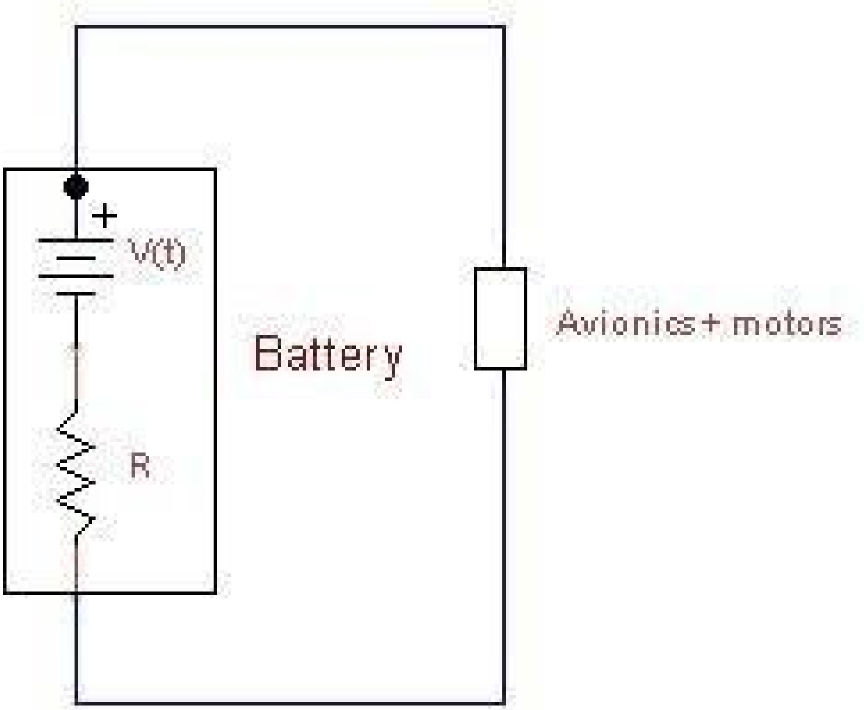

Figure 2.5: Electrical circuit schematized

The circuit can be schematized like in figure(2.5). This figure shows that the engine and the avionics form a dipole connected in series to the battery.

The *Avionics + motors* bipole is considered non-linear and keeps the Joule effect equation $P_{el} = VI = constant$ and substituting in it the battery voltage with the discharge curve equation, it will come out:

$$P_{el} = I_t - \left(-a \int_0^t I'_t dt' - RI_t + V_0 \right) = cost \tag{2.30}$$

By substituting $I_t = -\frac{dQ}{dt}$ and neglecting the term given by the effect of parasitic resistance, the previous equation is rewritten as:

$$(aQ_0 - V_0) \frac{dQ}{dt} - \frac{a}{2} \frac{d\left(Q^2\right)}{dt} = P_{el} \tag{2.31}$$

Now integrating result:

$$P_{el} t = (aQ_0 - V_0)(Q_t - Q_0) - \frac{a}{2} \left({Q_t}^2 - {Q_0}^2 \right) = P_{el} \tag{2.32}$$

With $aQ_0 - V_0 < 0$.

To calculate the battery capacity needed to ensure a flight of the desired time it must be replaced t with the autonomy and Q_t with $Q_0(1 - DOD)$.

$$Q_0 = \frac{V_0}{4aDOD} \left(1 - \sqrt{1 - \frac{8aP_{el}t}{{V_0}^2}} \right) \tag{2.33}$$

Knowing that part of electric power is consumed by the motors and the other from the rest of drone, it is possible to have the Pel by this equation:

$$P_{el} = n_{rot} \frac{P_{mec}}{\eta} + P_{others} \tag{2.34}$$

Where the P_{others} and can be estimate by the user knowing the mission, P_{mec} is calculated by the Renard's equation (2.16), η is the motors efficiency and n_{rot} is the number of rotors.

To estimate the battery mass, it can be observed that the mass of the batteries on the market [13] varies according to their capacity and the number of cells that compose them. In fact, the mass of the analyzed batteries is directly proportional to these two parameters. Considering m_0 as the mass of a single $3.7V$ and $1000mAh$ cell, it can be written

$$M = m_0 n_{cell} Q \tag{2.35}$$

With Q expressed in Ah.

Chapter 3

The Tool

In this chapter the developed tool is analyzed, indications will be provided to be able to use it and to understand what is calculated.

All the variables present in the various functions will be defined and how they work, the calculations performed and the relationships with the previously illustrated theory will be explained.

The present databases will be illustrated which allow to perform tool calculations having as input real data of components present on the market.

Finally, the output provided by the tool will be discussed and the elements useful for the construction of the drone will be identified.

3.1 The structure

The tool is divided into a main script and 9 blocks containing 9 different functions which in turn can be linked to sub-functions.

This structure is intended to facilitate modifications and optimizations, in fact a division of the tool into several functions and sub-functions allows you to vary the procedures that are used to determine essential parameters for another block without upsetting the entire structure, moreover it allows more developers to work on distinct blocks without overwriting each other's work.

The figure (3.1) shows how the tool is divided, how the blocks are composed and how them interact with the main and the other blocks.

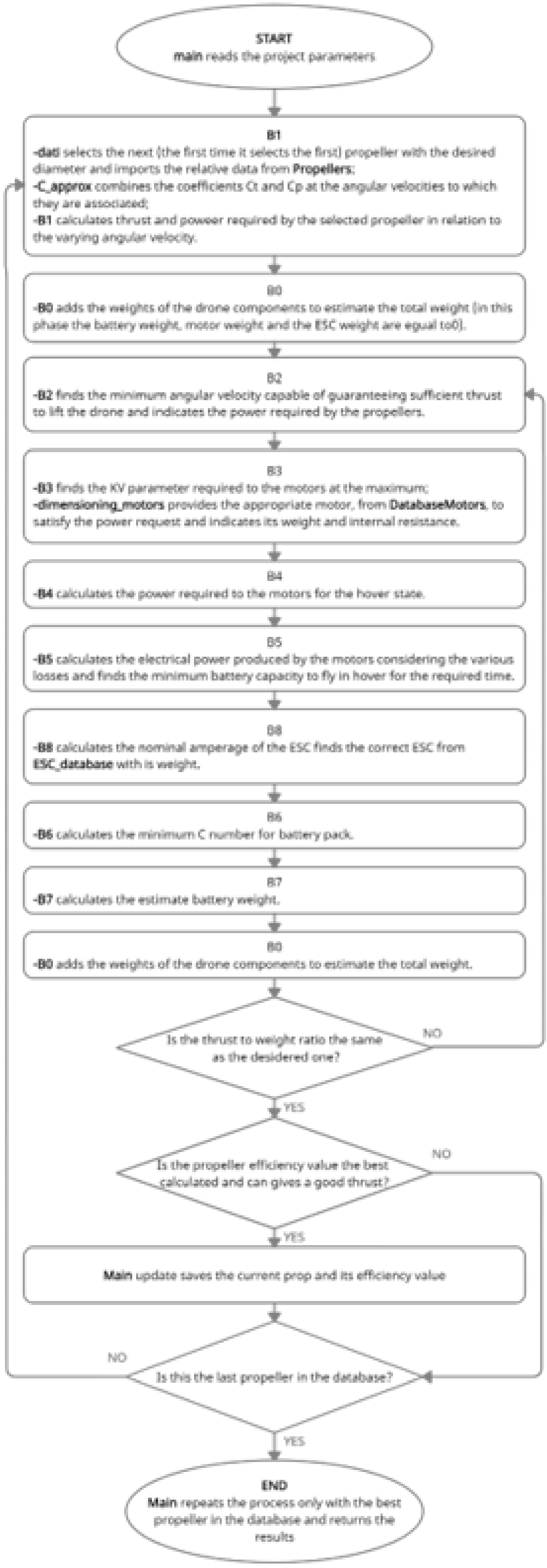

Figure 3.1: Tool structure

3.2 The *main.m* script

Variable or constant	**Unit of measure**	**Description**	**Output**
Ah_bat	Ah	Battery capacity in Ah	
Aut	s	Required autonomy in seconds	
Aut_min	min	Required autonomy in minutes	x
Avionics_M	kg	Avionics mass	
Bat_M	kg	Battery mass vector	x
C_bat		Battery C number	x
Controller	string	Controller selected	x
d	$inch$	Propeller diameter	
DOD	%	Battery degree of discharge	x
ESC_M	kg	ESC mass	
eta_aero_fin		Best propeller efficiency	
eta_aero		Propeller efficiency	
Frame_M	kg	Frame mass	
i		Iteration counter	
I_bat	A	Battery amperage	x
i_max		Iteration limitation	
I_nom	A	Nominal amperage	x
j		Iteration counter	
K_Imax		Max current limitation number	
KV	$\frac{rpm}{m/s}$	KV motor parameter	x
M_lim	M	Mach number limitation	
mAh_bat	mAh	Battery capacity in mAh	x
Mot_M	kg	Motor mass vector	
motor	string	Motor selected	x
n_blade		Number of blades for each propeller	
n_cell		Number of battery cells	x
n_P		Electric motors efficiency	
n_rot		Number of rotors	x

Variable or constant	**Unit of measure**	**Description**	**Output**
P_om	$[W, rad/s]$	Matrix of power and angular velocity	
Payload_M	kg	Payload mass	
Pel_av	W	Power consumed by avionics	
Pmec_hover	W	Mechanical power for hovering	
Pmec_max	W	Mechanical max power	
Pmec_tot	W	Total mechanical power in hovering	
pos_om_h		position index	
Power_h	W	Power required to each motor	x
Prop_M	kg	Propellers mass	
propeller	string	Propeller selected	x
r		Propellers with desired diameter	
R_mot	Ω	Motor resistance	
RPM	rpm	rpm required for hover	x
t		Propeller index	
T_om	$[kg, rad/s]$	Matrix of thrust and angular velocity	
Tot_M	kg	Total mass vector	x
TW_max		Max drone T/W	
TW_max_p		Max propeller T/W	
TW_max_fin		Best propeller T/W	x
TW_ratio		Desired T/W	
TW_tol		T/W tolerance	
u		index	
V_Amax	rad/s	Max angular velocity	
V_bat	V	Battery voltage	x

Table 3.1: *main.m* variables and constants

The main is divided into three parts: a first part allows the user to enter the values of variables and constants, the second part is the heart of the tool, here the various functions are called in order to obtain the desired outputs, which are shown to the user thanks to the last section of main.

The algorithm presents in the main provides an initial cycle for determining the most efficient propeller among the propellers in the database that allow the highest thrust to weight ratio for the proposed problem. The efficiency of the propeller is determined through the thrust to weight ratio in hover. To find this data, however, it is necessary to make the best coupling between each propeller and the other components sought. The coupling is carried out with an internal cycle that identifies at each iteration an engine, an ESC and a battery to be inserted in the drone and updates the calculation of the total weight which is compared with the previous value. The cycle is repeated until the total weight value coincides with the previous one, unless a tolerance is defined by the user.

In each iteration, it is checked that the value of the maximum thrust to weight ratio set can be reached by the drone with the propeller assigned, if not, this value is decreased by 0.1.

At the end of the internal cycle, it is assessed whether the propeller just evaluated is better than the previous one through a comparison of efficiencies and thrust to weight ratios.

After checking the results for all the propellers, the choice of components to be used only for the propeller chosen is made again and then the outputs are transmitted to the video.

3.3 The blocks

3.3.1 Block B0

The *B0.m* function

Variable or constant	**Unit of measure**	**Description**
Avionics_M	kg	Avionics mass
Bat_M	kg	Battery mass
ESC_M	kg	ESC mass
Frame_M	kg	Frame mass
Mot_M	kg	Motor mass
n_rot		Number of rotors
Payload_M	kg	Payload mass
Prop_M	kg	Propellers mass
TOT_M	kg	Total mass

Table 3.2: *B0.m* variables and constants

Block B0 consists of a simple operation that involves the sum of the mass of all components to calculate the total mass of the drone.
When it is called for the first time after that a propeller is selected, the battery mass, the motors mass and the ESC mass are equal to 0, those parameters take a value from the second time that B0 is used and they change at every cycle until a convergence, controlled through the T/W, is reached. The figure (3.2) shows how the total mass and the T/W change with each iteration.

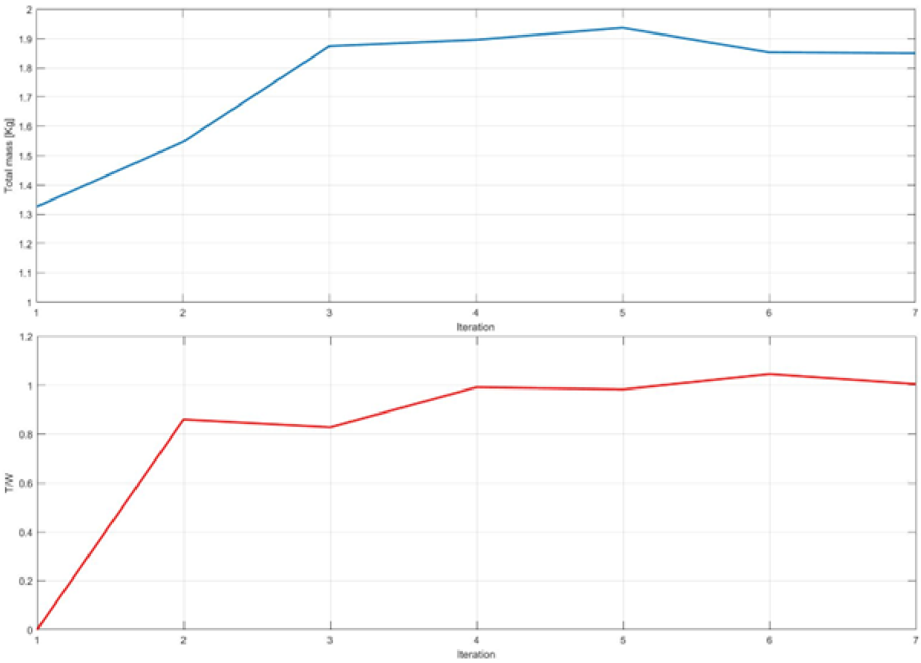

Figure 3.2: Mass and T/W variation during the iteration

The B0 block is used to carry out the check to stop the cycle that associates the other components with the propeller, also with this block one of the outputs of the entire tool is calculated, that is the total mass of the drone.

3.3.2 Block B1

The objectives of the block B1 is to provide the main with the selected propeller and its aerodynamic characteristics as the angular velocity of this varies.

In addition to the central function, this block includes two subfunctions and a database. (Figure 3.3)

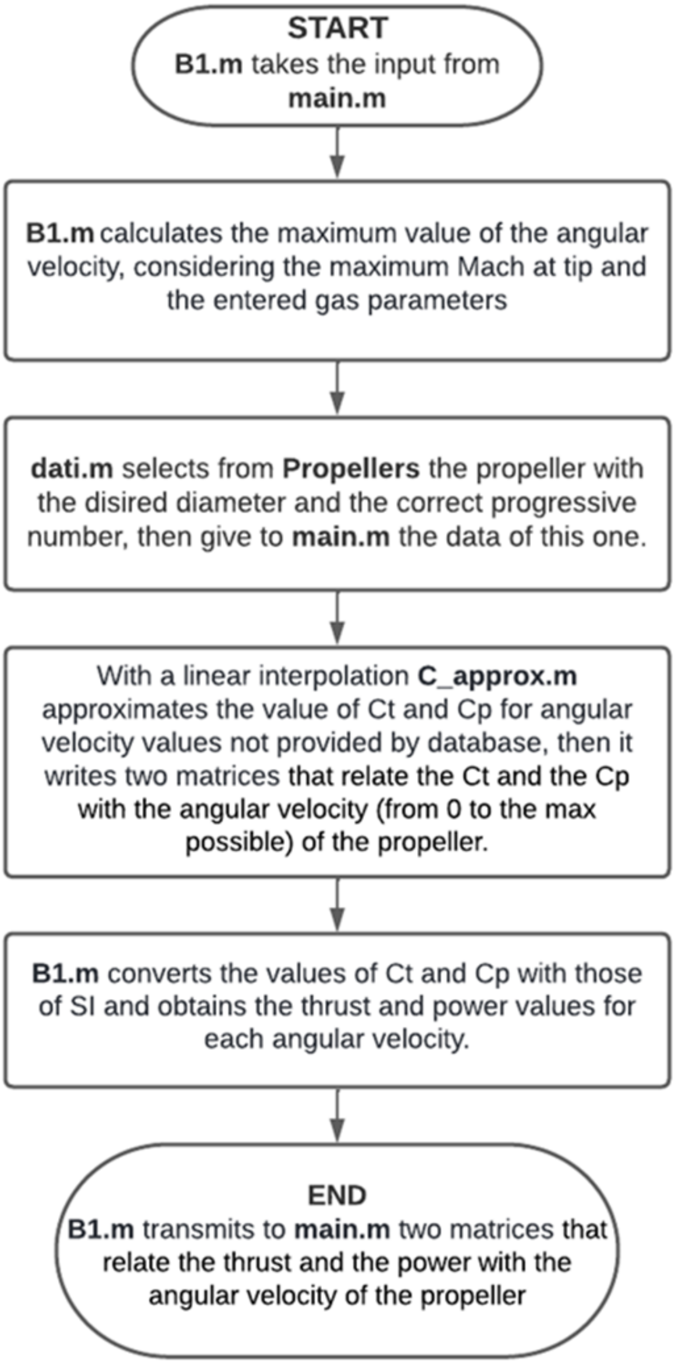

Figure 3.3: B1 structure

The *B1.m* function

Variable or constant	**Unit of measure**	**Description**
a		index
a_din	lb/in^3	Air density
C_p	$[ft^2/in^2rev^3, rad/s]$	Matrix of cp and angular velocity
C_t	$[ft/in \cdot rev^2, rad/s]$	Matrix of ct and angular velocity
c1	ft/in	conversion factor
c2	$N \cdot s^2/ft \cdot lb$	conversion factor
c3	Kg/N	conversion factor
c4	ft^2/in^2	conversion factor
c5	$lbf \cdot s^2/ft \cdot lb$	conversion factor
c6	$hp \cdot s/ft \cdot lb$	conversion factor
c7	W/hp	conversion factor
Columns		Vectors length
Cp	$[ft^2/in^2rev^3, rad/s]$	Matrix of cp and angular velocity
Ct	$[ft/in \cdot rev^2, rad/s]$	Matrix of ct and angular velocity
d	$inch$	Propeller desired diameter
dati_UIUC	Various	Propeller's data
DXP_om	$[W, rad/s]$	Matrix of power and angular velocity
DXT_om	$[kg, rad/s]$	Matrix of thrust and angular velocity
flag		Signal of stop iteration
Gamma		Cp/Cv gas ratio
i		Iteration
j		Iteration
M_lim		Mach number limitation
MM	kg/mol	Molar mass
n		Number of blades
om_max	rad/s	angular velocity limitation
p		Propeller index
P_om	$[W, rad/s]$	Matrix of power and angular velocity
Propoller	string	Propeller selected

Variable or constant	Unit of measure	Description
a		index
r		Numbers of propellers
R	$J/molK$	Gas universal constant
rads	rad/s	Angular velocity vector
T_om	$[kg, rad/s]$	Matrix of thrust and angular velocity
Temp	K	External temperature

Table 3.3: *B1.m* variables and constants

The central function provides that, after initializing the constants relating to the gas in which the user want the drone to fly, the angular velocity limit at the propeller is calculated, considering that at the tip the Mach number cannot be greater than 0.6, otherwise turbulence with negative effects on lift is established.

At this point, the databases relating to the rotor selected for the current iteration are imported using the *data.m* function.

Through a cycle, the function writes two matrices containing the values of C_t and C_p as the angular velocity increases. To do this, the function calls the subfunction *C_approx.m*.

Finally, with Renard's formulas (2.14)(2.16), the thrust and power required, as a function of the angular velocity, are calculated and are output after a series of unit conversions from the Anglo-Saxon ones (present in the database) to those of the SI.

The *Propellers.txt* database

Propellers.txt is a folder containing data relating to 249 propellers. Thanks to a database provided by the company *APC Propellers* [9], obtained through laboratory tests, it was possible to know the thrust and power coefficients of each propeller at all possible angular and forward speeds. In particular, the database provides the values of C_p and C_t of the propeller as the angular speed of the rotors and the speed of advancement of the drone vary. Since our study, for the moment, has focused solely on hover flight missions, the tool only uses the values referred to the speed of advance equal to 0. All data are reported through the Anglo-Saxon conventions of units, once imported, they therefore need a conversion to be used by the tool [10].

The *dati.m* subfunction

I/O	**Unit of measure**	**Description**
D	*inch*	Propeller desired diameter
Propeller	string	Propeller selected
dati_UIUC	various	Propeller's data
R		Propellers number
N		Number of blades
P		Propeller index

Table 3.4: *dati.m* inputs and outputs

This subfunction has the task of importing from the database the data of the helix to do the analysis.

To do this, knowing in input the diameter of the rotor and which is the progressive number of the one to be selected, it carries through a switch / case the textual data containing the aerodynamic characteristics of the propeller.

In output, in addition to the imported data, it also transfers the number of propellers in the database with the desired diameter and number of blades, so as to stop the analysis once the study of all possible rotors has been completed.

The *C_ approx.m* subfunction

I/O	Unit of measure	Description
om	rad/s	Angular velocity vector
C_p	$[ft^2/in^2rev^3, rad/s]$	Matrix of cp and angular velocity
C_t	$[ft/in \cdot rev^2, rad/s]$	Matrix of ct and angular velocity
om_max	rad/s	Max angular velocity
dati_UIUC	various	Propeller's data
flag		Signal of stop iteration

Table 3.5: *C_ approx.m* inputs and outputs

This subfunction selects from the data imported from *dati.m* those relating to the feed speed equal to 0 and the angular speeds between the first available and the ω_{max} determined in *B1.m* by limiting the speed to the tip of the blade.

C_ approx.m writes two matrices of 2 rows and 1000 columns are written that relate the C_t and the C_p with the angular velocity of the propeller.

The two matrices are output to the central function which converts them to the international measurement system.

3.3.3 Block B2

The *B2.m* function

Variable or constant	**Unit of measure**	**Description**
eta_aero		Propeller efficiency
n_rot		Number of rotors
om_max	rad/s	Max angular velocity
P_om	$[W, rad/s]$	Matrix of power and angular velocity
Pmec_hover	W	Mechanical power for hover
Pmec_max	W	Mechanical max power
pos_om_h		index
pos_om_max		index
ReqThrust	kg	Thrust required
T_om	$[kg, rad/s]$	Matrix of thrust and angular velocity
Tot_M	kg	Total mass
TW_max		Max drone's T/W
TW_ratio		Desired T/W

Table 3.6: *B2.m* variables and constants

This function compares the thrust of each propeller necessary to fly the drone (mass of the drone divided by the number of rotors) with the matrix that relates thrust and angular velocity of the propeller, finding at what angular velocity the flight of the drone is guaranteed.

The same thing is done to find the speed with which the desired maximum thrust is reached and finally through the power matrix the power required to reach the hover and that to reach the maximum thrust is searched.

Finally, the function calculates the efficiency of the propeller in the hover condition which will then be used to determine the best propeller.

3.3.4 Block B3

The objectives of the block B3 is to provide the main with the selected motor and its characteristics of mass and performance.

In addition to the central function, this block includes a sub-function and a database.(Figure 3.4)

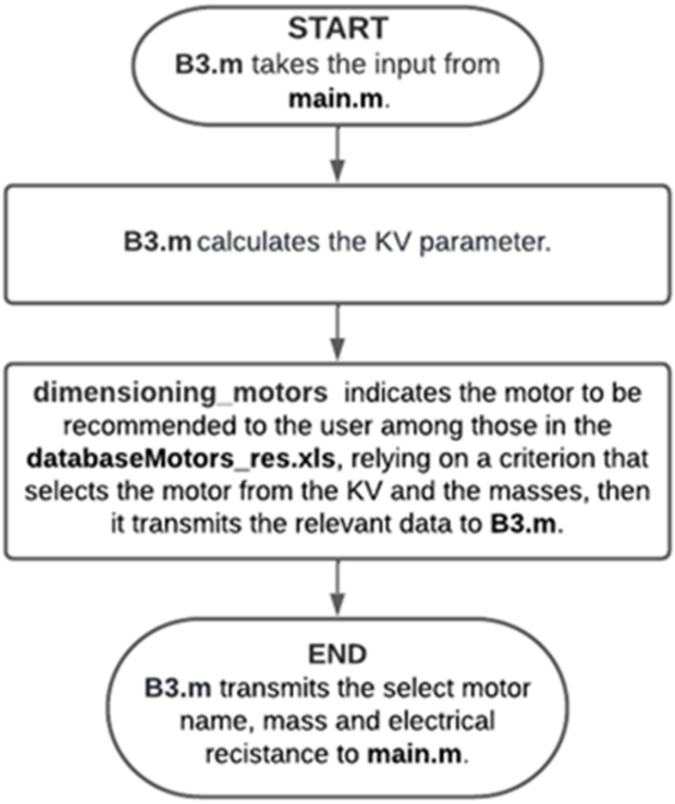

Figure 3.4: B3 structure

The *B3.m* function

Variable or constant	**Unit of measure**	**Description**
I	A	Max battery amperage
K_Imax		Max current limitation number
KV	$rpm \cdot s/m$	Motor parameter
Mot_M	kg	Motor mass
Motor	string	Motors selected
n_P		Motor efficiency
om_max	rad/s	Max angular velocity
Pmec	W	Mechanical max power
R_mot	Ω	Motor resistance

Table 3.7: *B3.m* variables and constants

The function *B3.m* calculates the KV parameter whit the equation (2.26) and then call the subfunction *dimensioning_motors.m* that, using the KV, selects the motor from a database.

Finally, the function outputs the motor name, resistance, mass and KV to *main.m*.

The *databaseMotors_res.xls* database

databaseMotors_res.xls is a motor database in excel format. It contains 278 different motors compatible with drones and actually present on market [11].

This database allows through a weighted choice based on the KV value and mass to choose the most suitable engine for a drone configuration.

In addition to the mass and the KV of the engine, the database provides the maximum power produced and the electrical resistance.

The *dimensioning_ motors.m* subfunction

I/O	Unit of measure	Description
KV	$rpm \cdot s/m$	Motor parameter
Mot_M	kg	Motor mass
Motor	string	Motors selected
R_mot	Ω	Motor recistance

Table 3.8: *dimensioning_ motors.m* inputs and outputs

The *dimensioning_ motors.m* function indicates the motor to be recommended to the user among those in the *databaseMotors_ res.xls*.

For the choice, the tool relies on a criterion that selects the motor that has the first KV lower than the input one (max (KV < KV desired)) among those that respect a mass limitation calculated by adding to the average of the masses of the motors with the KV included in a range of the desired KV is their standard deviation.

By doing so, the tool ensures the choice of an engine with sufficient performance and not high mass.

The name of the chosen engine, its mass and its resistance are provided in the output.

3.3.5 Block B4

The *B4.m* function

Variable or constant	**Unit of measure**	**Description**
n_rot		Number of rotors
Pmec	W	Mechanical power for hover
Pmec_tot	W	Total mechanical power for hover

Table 3.9: *B4.m* variables and constants

The block calculates the total mechanical power required by the propellers to the motors to fly in hover by multiplying the power required by the single rotor by the number of rotors present.

In this hover flight analysis, it was assumed that each motor provides the same power to keep the drone in balance. In the case of translated flight or interaction with external forces, the flight controller will have to calibrate the powers to be supplied to each propeller of the drone to ensure the correct flight attitude.

3.3.6 Block B5

The *B5.m* function

Variable or constant	Unit of measure	Description
Ah_bat	Ah	Battery capacity in Ah
Aut	s	Required autonomy in seconds
Aut_h	h	Required autonomy in hours
DOD		Battery degree of discharge
n_P		Electric motors efficiency
Pel_av	W	Power consumed by avionics
Pel_mec	W	Electric used by motor
Pel_tot	W	Total electric power
Pmec	W	Mechanical power for hover
V	V	Battery voltage

Table 3.10: *B5.m* variables and constants

This function is used to calculate the required capacity of the battery.

The function finds the power supplied to the motors by dividing the power required by the rotors by the efficiency of the motor at the hover speed and adding the power required by the other components of the drone (which is supplied by the user in input).

Finally, the formula (2.33) previously obtained is used to find the battery capacity needed by the drone. The DOD and the autonomy of flight are imposed by the user in the main, depending on the mission he wants carry out.

3.3.7 Block B6

The objectives of the block B6 is to provide the main with the selected electronic speed controller, its mass and its nominal current.

In addition to the central function, this block includes a database.

The *ESC_ database.xls* database

ESC_ database.xls is a motor database in excel format.

This database, filled with the ESCs present in the *eCalc* tool, contains 260 different electronic speed controllers compatible with drones and actually present on the market [11].

The database is able to provide the peak and nominal currents of each ESC, its mass and its electrical resistance.

The *B6.m* function

Variable or constant	**Unit of measure**	**Description**
Controller	String	Name of the ESC selected
ESC_M	kg	ESC mass
I	A	Vector of ESC models amperage
I_esc	A	Actual ESC amperage
I_nom	A	Nominal current
M	kg	Vector of ESC models mass
Model	String	ESC models name
Pel_max	W	Max electrical power
Pmec_max	W	Max mechanical power required
R_mot	Ω	Motor resistance
rend_max		Motor efficiency at max torque
toll	A	Tolerance

Table 3.11: *B6.m* variables and constants

Set to 0.6 the efficiency of the motor in regime of maximum torque supplied, the function calculates the maximum power required and then the nominal amperage required by the motors.

Then using this data in a cycle, finds the lightest ESC in the *ESC_ database.xls* that controls an amperage like and greater than the desired one.

The nominal current, mass and name of the chosen ESC are provided in the output.

3.3.8 Block B7

The *B7.m* function

Variable or constant	**Unit of measure**	**Description**
Ah	*Ah*	Battery capacity in Ah
C_bat		Battery discharge rate numbers selected
C_bats		Classic LiPo battery C numbers
I_nom	*A*	Battery nominal amperage
n_cell		Number of battery cells

Table 3.12: *B7.m* variables and constants

This function selects the rates of discharge of the battery. These parameters are very important to the correct operation of the tool, because the autonomy of flight and the battery capacity (so the battery mass) are very influenced by them.

Knowing the nominal amperage at which the ESC works and the capacity, the tool calculates the minimum discharge rate necessary.

At this point, in a matrix containing the possible combinations of average and maximum C rate of the batteries on the market, the tool finds the minimum combination that guarantees an average C rate higher than the one previously calculated.

3.3.9 Block B8

The *B8.m* function

Variable or constant	Unit of measure	Description
Ah	Ah	Battery capacity in Ah
bat_M	kg	Battery mass
ind		Index
list	Ah	List of most common battery capacity
n_cell		Number of battery cells

Table 3.13: *B8.m* variables and constants

This function aims to provide the mass of the battery that will be mounted on the drone.

Knowing the classic values of the battery capacities on the market, the tool selects the one closest to the capacity required by the drone.

At this point, through an the empirically found function (2.35) that estimates the mass of a battery based on its capacity, the mass of the battery with the indicated capacity is found.

3.4 Output

At the end of the main a series of strings have been inserted which provide the results obtained by the tool as output.

In particular, some of the parameters that the user has entered are summarized in order to help him in a quick check of the inputs provided, the selected components are shown with the parameters that characterized their choice (if you do not want to buy the selected component, please can check the compatibility of a component with more performing specifications) and shows what the overall mass of the drone will be with the selected components and the payload inserted.

Chapter 4

Test phase

To validate the tool only two different approaches were used:

- compare the results of TRIDENT with the *eCalc* tool, inserting the outputs found in the online software;
- test the flight autonomy of the drones that the team owns and check compatibility with the value provided by TRIDENT.

4.1 Comparison with *eCalc*

To compare TRIDENT with *eCalc*, the software that Draft Polito has always used for the construction of drones, it was decided to invent as many mission cases as possible and to calculate the suggested components to be assembled using the developed tool.

At this point, the components supplied by TRIDENT were entered as input on *eCalc* and the results supplied by *eCalc* were compared with the values initially entered in the main tool.

Below is one of the comparisons between the input and the output of the two tools.

An example of comparison between TRIDENT and *eCalc* results

TRIDENT input The following input parameters are arbitrarily entered into the tool:

- Payload mass = $500Kg$
- Number of rotors = 4
- Number of blades per rotor = 2
- Propeller diameter = $10inch$
- DOD = 85%
- Flight autonomy = $18min$
- Max T/W = 3

TRIDENT output The tools output, without errors or warnings, the results in figure (4.1).

```
.....................................................................
 RESULT :
Estimated Tw ratio at the next conditions:              1.0 g
Number of rotor:                                          4
Propeller:                                            10x47SF
Indicated KV:                                          1153 min^{-1} V^{-1}
Recommended motor brand:                               F100_1100
RPM @ hover:                                           6723 RPM
Hovering power per motor:                                74 W
Estimated single motor weight:                           67 g
ESC Continuous current:                                58.9 A
Recommended ESC (controller):                         CC Phoenix Edge HV 60
Number of battery cells:                                  4
Battery capacity:                                      7963 mAh
C-rate:                                          45/    60
Autonomy:                                                18 min
Total battery voltage:                                 14.8 V
Total battery recistance:                               1.9 mΩ
Battery amperage:                                        21 A
DOD:                                                   85.0 %
Estimated battery weight:                               800 g
Estimated total mass:                                  2195 g
Max possible T/W ratio:                                3.00
```

Figure 4.1: Test 1 TRIDENT

From the TRIDENT output it is possible to extrapolate the input parameters to be entered on *eCalc*:

- number of rotors = 4
- propeller: *APC 10x47SF*;
- Motor: *F100_1100*;
- ESC: *CC Phoenix Edge Hv 60*;
- number of battery cells: 4;
- battery: $8000mAh45/60$;
- DOD:
- total mass: $2195g$.

Comparison with *eCalc* By entering the parameters just found as input on the *eCalc* site and launching the tool, the results in figure (4.2) are obtained.

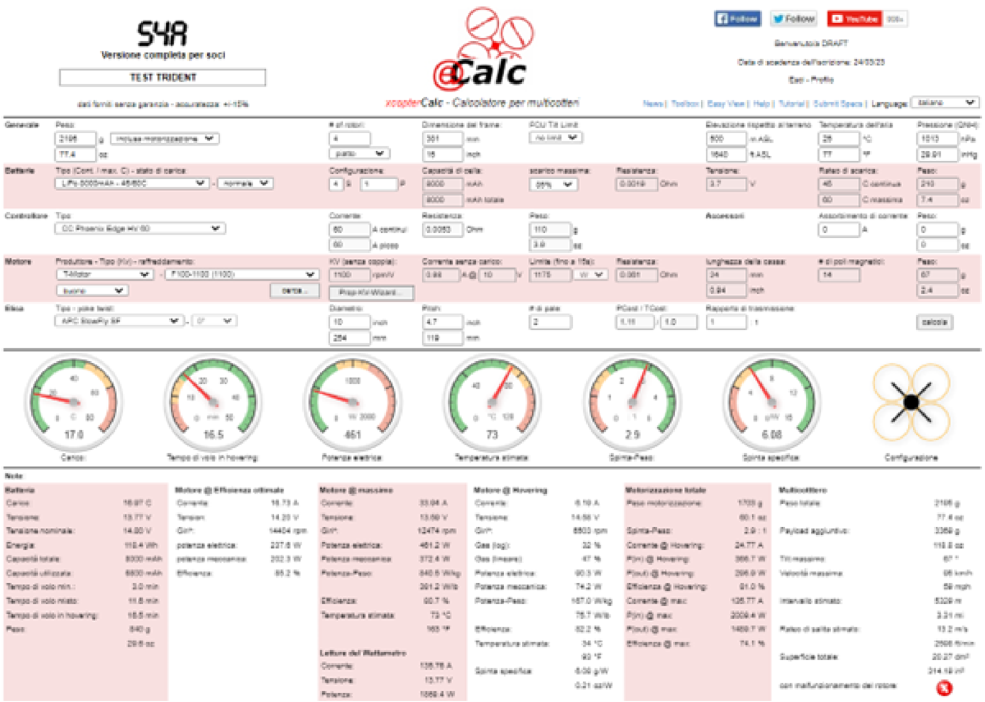

Figure 4.2: Test 1 *eCalc*

The results obtained show the autonomy of flight in hover, the number of revolutions per minute in hover and the maximum T / W.

As far as RPM and maximum T / W are concerned, the results are very close to those calculated by the tool, in fact an accuracy greater than 95% is highlighted.

As far as the flight autonomy is concerned, this is incorrect by 1.5 minutes. This disparity is motivated by the fact that *eCalc* underestimates the autonomy of the drone as indicated in the site guidelines and as confirmed by the team members who have already used the software and tested the drones built.

Nevertheless, the data has an error of 9% and remains within the limits of accuracy indicated by the program developers (15%).

4.2 Flight autonomy test

To validate the tool, forced simulations were carried out so that the components of the drones that the team Draft PoliTo already owned were recommended in the output and the actual payload and autonomy in hover (tested by the team) indicated in input.

Once the mass of the drone was measured and the components used were verified, the propellers and motors with characteristics similar to those desired were obscured in the databases, finally through an iterative process in which the duration of the flight was varied, it was match the battery capacity and the mass with those of the drone.

The tests were carried out with 3 different drone configurations and have always confirmed the calculations made by the tool with an accuracy of over 95%.

Below is one of the comparisons with the field tests carried out: *Nyx* , 14/04/2022.

4.2.1 *Nyx* , 14/04/2022, Politecnico di Torino

Nyx is the one designated for this year's *Leonardo Drone Contest*. For the team it is very important to extend the drone's autonomy to the maximum, as in the race it will be granted a limited period to carry out some missions and a shorter battery life can limit the number of tests available, due to the time used to replace the part.

The test carried out on this drone allows you to validate the calculations made by the drone, verifying if the real and calculated autonomies coincide between drones with the same components. In a second analysis it was possible to verify if there had been weight / size / motor / battery / ESC configurations that would have guaranteed greater efficiency and / or autonomy.

Drone configuration

The *Nyx* configuration on test day is shown below.

- Propellers: *APC 10x45MR*
- Motors: *SUNNYSKY X2212-12 (KV 980) III*
- Battery: $6000mAh$ 4s
- ESC: $50A$
- Total mass: $2183g$

Test Day

During an outdoor test session of *Nyx*, a fully charged battery has been fitted to the drone and it started to fly at 2 meter above flow. The weather conditions were stable and unventilated, this allowed the drone not to waste a lot of energy in flight control, which would have compromised the test.

We decided to stop the flight of the drone when the battery reached 15% charge, this was possible thanks to a remote voltage control. So after 17 minutes and 15 seconds of hovering, the drone landed.

Figure 4.3: Test 2 Photo of the test day

Tool validation

To verify the correct functioning of the tool, an inverse check was conducted.

In fact, the tool allows you to force the choice of components by hiding the others in the database, in doing so you can find the autonomy of the drone.

To do this, you need to change the payload mass and autonomy values until the total mass and battery capacity of the drone coincide with the actual one.

To be in line with the flight data, a DOD of 85% has been entered.

```
......................................................................
 RESULT :
Estimated Tw ratio at the next conditions:              1.0 g
Number of rotor:                                          4
Propeller:                                             10x45MR
Indicated KV:                                           983 min^{-1} V^{-1}
Recommended motor brand:                                X2212-12-980-III
RPM @ hover:                                            5987 RPM
Hovering power per motor:                                 60 W
Estimated single motor weight:                            56 g
ESC Continuous current:                                 45.3 A
Recommended ESC (controller):                          Leomotion LC50 SLIM LV
Number of battery cells:                                  4
Battery capacity:                                       5975 mAh
C-rate:                                           45/    60
Autonomy:                                                 18 min
Total battery voltage:                                  14.8 V
Total battery recistance:                                1.5 mΩ
Battery amperage:                                         21 A
DOD:                                                    85.0 %
Estimated battery weight:                                600 g
Estimated total mass:                                   2174 g
Max possible T/W ratio:                                 2.50
```

Figure 4.4: Test 2 TRIDENT

The figure (4.4) shows the output given by the tool when, at the end of the iterations, the battery capacity and the total mass are similar at the real case.

It can be seen that the motor and the propeller selected by the tool coincide with those of *Nyx*, as was necessary to validate the tool. In this case also the ESC is in line with the one used, as it is recommended one that regulates the current to a maximum of $50A$.

The flight autonomy of the aircraft is 18 minutes, slightly higher than in the real case, but with an error of 4%. This may be due not only to the various approximations made during the calculation, but also to the fact that the test was carried out outdoors and, although there was no consistent wind, the drone was subjected to small atmospheric forces impossible to calculate at priori from the tool.

It can therefore be said that the tool has carried out an excellent analysis of the problem, providing a result in line with the flight test performed.

Configuration suggested by the tool

Once the validity of the tool was demonstrated, it was possible to verify if the *Nyx* configuration was the most efficient. Using the engines and propellers complete database, a simulation was launched that guaranteed the same autonomy of the drone, the same maximum thrust - weight ratio and the same frame size. The tool, as the figure (4.5) shows, suggests a different propeller - motor - battery combination.

```
..............................................................................
 RESULT :
Estimated Tw ratio at the next conditions:               1.0 g
Number of rotor:                                           4
Propeller:                                            10x38SF
Indicated KV:                                           1334 min^{-1} V^{-1}
Recommended motor brand:                              T2216 Pro²
Numero di giri per mantenere una condizione di hover:   5081 RPM
Hovering power per motor:                                 45 W
Estimated single motor weight:                           129 g
ESC Continuous current:                                 49.9 A
Recommended ESC (controller):                         Leomotion LC50 SLIM LV
Number of battery cells:                                   4
Battery capacity:                                       4363 mAh
C-rate:                                            45/   60
Autonomy:                                                 18 min
Total battery voltage:                                  14.8 V
Total battery recistance:                                1.5 mΩ
Battery amperage:                                         21 A
DOD:                                                    85.0 %
Estimated battery weight:                                400 g
Estimated total weight:                                 2266 g
Max possible T/W ratio:                                 2.50
```

Figure 4.5: Test 2 New possible *Nyx* configuration 1

A further analysis was also carried out which showed that the drone could have resisted in flight longer if the same components had been used, varying only the propellers used, which are not optimal for this configuration. In figure (4.6) it can be seen how by changing even this component alone, the drone gains 3 minutes of autonomy.

```
...........................................................................
 RESULT :
Estimated Tw ratio at the next conditions:              1.0 g
Number of rotor:                                          4
Propeller:                                           10x38SF
Indicated KV:                                         983 min^{-1} V^{-1}
Recommended motor brand:                             X2212-12-980-III
Numero di giri per mantenere una condizione di hover:  5493 RPM
Hovering power per motor:                               67 W
Estimated single motor weight:                          56 g
ESC Continuous current:                               45.3 A
Recommended ESC (controller):                        Leomotion LC50 SLIM LV
Number of battery cells:                                  4
Battery capacity:                                     5998 mAh
C-rate:                                          45/   60
Autonomy:                                               21 min
Total battery voltage:                                14.8 V
Total battery recistance:                              1.5 mΩ
Battery amperage:                                       21 A
DOD:                                                  85.0 %
Estimated battery weight:                              600 g
Estimated total weight:                               2174 g
Max possible T/W ratio:                               2.50
```

Figure 4.6: Test 2 New possible *Nyx* configuration 2

These analyzes carried out well explain the usefulness of the tool and its fields of application. In particular, if the team had had the tool available from the very beginning of *Nyx*'s design, they could have known which components were recommended to be used immediately, saving time in testing multiple configurations both through existing tools and in flight tests. In addition, the team could have saved the cost of components or make the most of those available, by building a drone with greater autonomy.

Chapter 5

Future developments

TRIDENT is a tool still under development, there are still many improvements that can be made. In the end of this academic year, after a brainstorming some ideas to improve the tool came out.

It has already been thought of wanting to input more complete data regarding the mission to be carried out, for example we are starting to study how to provide the possibility to choose to undertake maneuvers, accelerate and brake. The propeller database that we have allows to know the C_p and C_t of the propellers as the speed of advancement varies, for this reason a model has already been set that allows you to create a function that provides the thrust required when the speed of advancement of the blades varies, so as to be able to calculate the power required by the engine and the consumption of the battery.

Another possible development will be that of studying the distribution of masses in the drone and the consequent thrust variations for each engine. Through this development it will be possible to provide the manufacturer even more information, to avoid construction errors that would affect the performance of the drone.

It will also be necessary to include the possibility of using counter-moving blades. This analysis has not yet been carried out, but it is necessary as it would open the way to many more situations in which the payload is large and the thrust of 4 propellers is not enough (in the case of a classic x configuration) and it is necessary to insert counter-rotating blades. that do not increase the space occupied by the drone. This study moves away from the mechanics of simple flight as it sees antagonistic forces coming into play that influence each other. It will therefore be necessary to vary the B1 block and calculate the thrust in a different way, laboratory tests are also provided to verify the effective thrust of a pair of counter-rotating blades.

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