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**A Fixed-wing UAV Capable of
Vertical
Take-off and Landing for Aerial
Mapping and Photogrammetry.**

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como requisito para a aprovação da disciplina:*

DAS 5511: Projeto de Fim de Curso

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Este relatório foi julgado no contexto da disciplina
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Orientador

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Fly, you fools!

J. R. R. Tolkien

Resumo

Mapeamento aéreo é uma das tarefas que foi revolucionada com a chegada dos drones nos últimos anos. O trabalho manual de tirar fotos, organizá-las e juntá-las mudou para colocar coordenadas em um software, e as fotos resultantes em outro para o pós-processamento após o vôo.

Dependendo da tarefa em questão, o operador pode escolher utilizar multirotore para áreas menores, ou uma aeronave de asa fixa para as maiores. Enquanto multirotore são precisos e podem pousar/decolar de virtualmente qualquer lugar, sua autonomia sofre, uma vez que todo o empuxo para mantê-los em vôo é gerado diretamente pelas hélices. Aeronaves de asa fixa, por outro lado, podem cobrir grandes áreas rapidamente como um consumo energético menor, mas são mais difíceis de posicionar e podem requerer dezenas de metros para pouso e decolagem.

Este trabalho propõe o desenvolvimento de uma aeronave entre estes dois mundos. O protótipo projetado é uma aeronave de asa fixa *tail-sitter*, capaz de decolar na vertical como um multirotor e transicionar para o modo de vôo asa fixa para maior eficiência, habilitando a cobertura de grandes áreas sem necessitar de aparelhos adicionais para pouso e decolagem, nem de amplos espaços. 

Palavras-chave: tail-sitter, aerofotogrametria, VANT.

Abstract

Aerial mapping is one task that got revolutionized by the arrival of drones on the latest years. The manual job of taking pictures, printing and assembling them together was changed into putting coordinates into a software, and the pictures into another after the flight.

Depending of the task at hand, the operator can chose a multirotor for smaller areas, or a fixed-wing aircraft for larger ones. Both categories have their quirks: While multirotors are precise and can take-off/land virtually anywhere, their autonomy suffers as they generate all their lift by using propellers, Fixed-wing aircraft, on the other hand, can cover large areas quickly with a smaller power consumption, but are harder to position, and require larger areas for take-off an landing.

This work proposed an aircraft in between these two worlds. The prototype designed is a tail-sitting fixed-wing aircraft, able to take-off as a multirotor and transition into fixed-wing mode for more efficiency, enabling it to cover larger areas while needing a small area for take-off or landing and no additional apparatus for take-off.

results!

Keywords: tail-sitter, aerophoogrammetry, UAV.

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1 Introduction

1.1 Novarum Sky

Novarum Sky is a still young company, created in 2014 and based in Florianópolis-Brazil. It develops aerial technologies for both manned and unmanned systems, including long-range digital audio/video transmission solutions, real time kinematics for precise localization during inspections and mapping, and inspections systems themselves.

The company was featured on Web Summit 2017 Lisboa, and has it's main partners currently in Europe, with ongoing negotiations with MikroKopter and EDP.

1.2 Motivation

Technology and automation have been changing and improving a lot of tasks on last few decades. One of the tasks is aerial mapping, which started with balloons, then manned airplanes, and now, for smaller areas, is being increasingly done with drones [1].

For the company, this project might mean a new innovative product, as it has both advantages of fixed-wing and rotary-wing aircraft. Such product means there's no need for long landing stripes, nor for relatively expensive equipment such as landing parachutes. The competition is also low, as fixed wings are currently a niche market, compromising around 3% of the photogrammetry solution by DroneDeploy [2].

In the context of Automation and Control Engineering, this project entails most of the areas discussed, such as mechanics, electronics, manufacturing, fast prototyping, and control of dynamic systems.

1.3 Objectives

The final objective of the work is to have a working prototype of a VTOL fixed-wing UAV able to autonomously take off vertically, transition into fixed-wing mode, follow a planned path taking pictures, transition back into hover mode, and land autonomously. It's planned to have a smaller prototype to test and tune the hover mode before testing the larger, heavier and more powerful final prototype, for safety and practicality reasons. The possible on-board electronics will be briefly described and one of them chosen. An overview will be given of the control systems in place and their tuning. The requisites for the job will be gathered, and the electromechanical structure designed and built around it. It's expected that the prototype fulfills the hole between rotating-wing and fixed-wing

aircraft by being able to land in tight spaces, while having a performance close to that of fixed-wing aircraft.

1.4 Requisites

For the design, a few conditions have been imposed by the available material and desired performance:

- The flight time should be atleast 1 hour.
- The cruise speed should be around $15m/s$.
- The batteries used will be 6s lithium-polymer packs of 4500 mAh or 4s packs of 10000mAh.
- The motors should preferably be the ones already in use at the company, MK3538, Mk3638, or MK3644
- The UAV must be able to take of and land autonomously.

1.5 Structure

This report is structured in XX chapters. Chapter 1 gives an introduction to the finalize report. Chapter 2 describes the fields of aerial mapping and photogrammetry. Chapter 3 delves into the flight mechanics and the UAV's mechanical design. Chapter 4 shows the electronics involved. Chapter 5 shows the control structure and it's tuning. Chapter 7 details the validation process, the tests performed, and the results obtained.

2 Aerial Mapping and Photogrammetry

2.1 The need for mapping the land

The first known map (actually a painting of a city) dates up to the 7th millennium BCE, [3], while the oldest surviving world maps are from 9th century BCE Babylonia [4].

In the past, maps were used mostly for localization and navigation [citation needed]
and were made without special tools, mainly by sight. During the Age of Exploration, new
tools such as the sextant and magnetic compass helped improve accuracy, while remaining
as a navigational tool.

On the last centuries, maps began being used to precisely map properties, natural
landscapes, and cities, and used as a tool of government [5]. Mapping properties, for ex-
ample, requires high dimensional accuracy, hard to get with regular tools. This is usually
the job of land surveyors, professionals who use a multitude of tools, such as total sta-
tions, robotic total stations, GPS receivers, retro reflectors, 3D scanners, radios, handheld
tablets, digital levels, subsurface locators, drones, GIS, and surveying software.

2.2 Aerial Mapping

Aerial mapping consists of using photographs taken from the air, usually with
the camera facing straight downwards, correcting the perspective transformation, and
assembling them into an orthomosaic, as seen on Figure 1.

2.3 Aerophotogrammetry

Aerophotogrammetry takes the job one step further. By knowing the cameras lens
intrinsics, software are capable of matching a number of pictures, detecting features on
the environment, and locating the point used to take each of the pictures, this process
is called multi-view stereo. With this information, it's possible to rebuild in 3D most of
the environments, enabling the operator to interact with the area as a 3D mesh. By using
precise GPS information(such as RTK/PPK data, or total stations) or known landmarks,
it's possible to accurately measure distances, areas, volumes, angles and elevations, simpli-
fying the surveyors' job. Aerophotogrammetry can also be used to rebuild in 3D buildings
and other structures, enabling precise calculations of volume and distances, allowing the
use of 3D models on CAD software for faster and easier construction and planning. It



Figure 1 – Orthomosaic. source: Indonesian Redcross/OpenAerialMap

allows, for example, the calculation of displaced volume on a quarry, or how much landfill is required to level some terrain.

The results of an open-source multi-view stereo pipeline implementation usint openMVS [6] and openMVG [7] can be seen on figures 2 and 3. On figure 2 the software shows the cameras found, and their relative positions on the map. The orange areas are locations not covered by the cameras. It is important to notice that, as the coverage is does not catch every angle of the structures, some deformations are expected, especially on hidden areas. Figure 3 shows the rebuilt and textured 3D model.



Figure 2 – Identified camera positions on "Oblique mapping of a village" dataset



Figure 3 – 3D reconstruction visualization of the "Oblique mapping of a village" dataset.

3 Flight Mechanics and Design

3.1 Brief Introduction to Flight Mechanics

Flight mechanics deal with a vehicles interaction with propulsional, aerodynamic, and gravitational forces.

In order to achieve proper flight, a vehicle needs an upwards force, and means of maneuverability. the former is usually generated by the means of a propeller, while the latter can be either the result of spinning propellers, or using control surfaces to deflect the passing air movement, causing a force to the opposite direction. This field of mechanics deals with the study of vehicle trajectories (performance), stability, and aerodynamic control.

3.2 Fixed-Wing Mechanics

In fixed-wing aircraft, air flowing through the wings generates a pressure differential, usually lowering the pressure on top of the wing, generating a force usually called "lift", the force responsible for canceling the gravitational pull and keeping the vehicle aloft in the air.

In a simplified explanation, two main principles are responsible for generating lift:

3.2.1 Flow deflection and Newton's laws

Most wings have an angle of attack (to be hereafter called α) such that $\alpha > 0$, which means the air passing through it gets deflected down. According to Newton's second law, an opposite force is necessary on the wing. This force is the generated lift.

3.2.2 Increased flow speed and Bernoulli's principle

Bernoulli's principle states that within a steady airflow of constant energy, when the air flows through a region of lower pressure it speeds up and vice versa. Implying there is a direct mathematical relationship between the pressure and the speed, meaning if one knows the speed at all points within the airflow, one can calculate the pressure and vice versa. For a cambered airfoil (where the chord at the top is longer than the chord at the bottom) the/home/will/Pictures/Screenshot from 2017-11-13 11-03-27.png air needs to take a longer path, moving faster, thus lowering the pressure on the top, and generating lift.

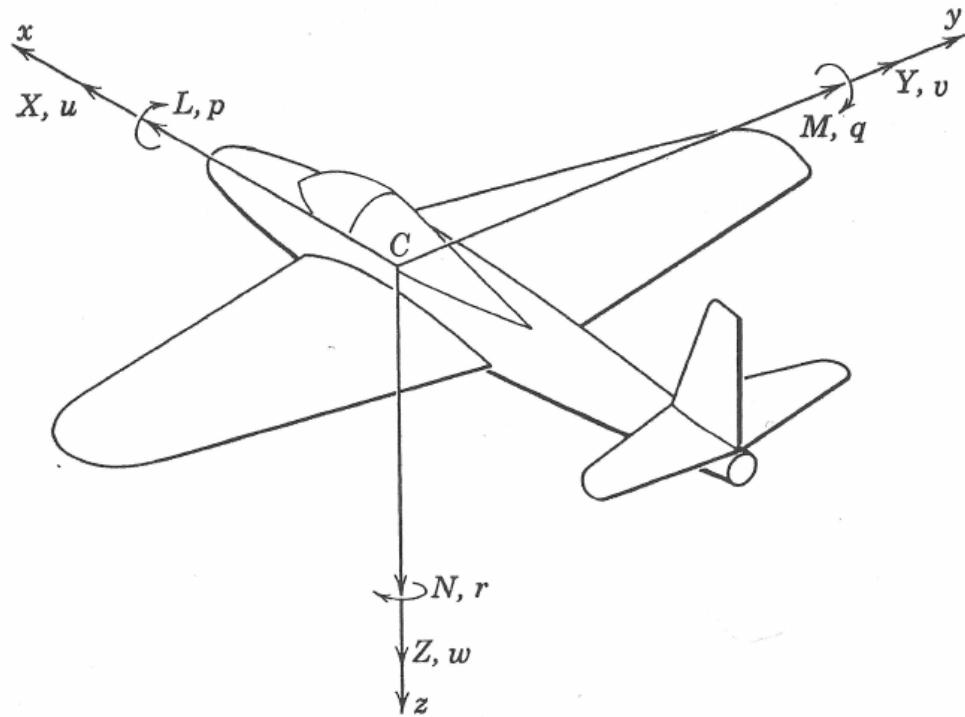


Figure 4 – Coordinates system and relevant variables.

3.2.3 Airfoil Shape

How much lift is generated depends on the chosen airfoil. An cambered airfoil (longer chord on the upper surface than in the lower one) generated lift even when the angle of attack α is zero. Symmetric airfoils need a positive angle, and the lift is generated by deflecting the air downwards. Other properties that depend on the airfoil shape are the drag (air force pushing against the direction of movement) and angular moment it generates on the aircraft.

3.2.4 The Coordinate System and Nomenclature

The coordinate system, when dealing with the fixed-wing mode, is as shown in figure 4

Where:

- x, y , and z are the coordinates, with the origin in the vehicle's center of mass.
- u, v , and w are the linear velocities in each of the x, y , and z coordinates, respectively.

- X , Y , and Z are the components of the aerodynamic force in each of the x , y , and z coordinates, respectively.
- p , q , and r are the linear velocities in each of the x , y , and z coordinates, respectively.
- u , v , and w are the linear velocities in each of the x , y , and z coordinates, respectively.
- Although not indicated in the figure, the variables ϕ , θ , ψ represent the angular rotations, relative to the equilibrium state, about the x , y , and z axes, respectively. Thus, $p = \dot{\phi}$, $q = \dot{\theta}$ and $r = \dot{\psi}$ where the dots represent time derivatives.
 ϕ , θ , and ψ can also be referred, respectively, as *roll*, *pitch*, and *yaw*.

3.3 VTOL Mechanics

When in VTOL mode, the coordinate system used is similar to that in a conventional multirotor, with Z pointing up parallel the motors axis, and X going throughb the fuselage, pointing away from the belly of the aircraft.

The mechanics involved in vertical take-offs and landings is slightly different. The lift generated becomes meaningless, no more than a slight perturbation to the system. The generated thrust becomes directly responsible for vertical motion and roll control, while the control surfaces can redirect the airflow allowing control of yaw and pitch.

An approximate model can be seen on [?], however, as this work does not focus on the dynamics or control itself, it is not detailed here.

3.4 XFLR5

XFLR5 is an analysis tool for airfoils, wings and planes operating at low Reynolds Numbers. It includes:

- Xfoil's Direct and Inverse analysis capabilities;
- Wing design and analysis capabilities based on the Lifting Line Theory, on the Vortex Lattice Method, and on a 3D Panel Method.

This tools enables the iterative design and analysis of multiple aircraft configurations.

elaborar
aqui



Figure 5 – Zagi 12 airfoil.

3.5 Design

The chosen design is the one of a flying wing, a fuselage-less made of a wing, propulsion system, and control surfaces. The reasons are because of a simpler and sturdier mechanical structure, besides the possibility of the VTOL configuration

3.5.1 Preliminar Design

As a starting point, a wing with a central hub and 2 semi-wings ending in symmetrical winglets was designed. The ZAGI12 airfoil was chosen due to it's good soaring capabilities and low stall speed .

With the airfoil chosen, It's characteristics were calculated with the aid of XFOIL, an airfoil analysis tool built into XFLR5.

citation
needed

These characteristics plots can be seen on figure 6.

It can be noted that the point with the highest C_l/C_d ratio, the theoretical point with better lift to drag ratio, and therefore best gliding performance. It's also notable that the airfoils moment "pulls" it into this better C_l/C_d ratio, allowing the aircraft to fly into this ideal condition without deflection of the control surfaces

With that data, the main body was conceived, as seen in the figure 7. With this CAD tool we can then analyze the performance of the aircraft as a whole. This gives us the same data as the airfoils', but for the whole craft, as seen in figure 8.

Some data can be inferred from these graphs. From 6 it can be seen that the highest C_l , or Lift Coefficient, is obtained around $\alpha = 8$ deg, which, possibly by design of the airfoil, is also the zone with a higher C_l/C_d , or *lift-to-drag ratio* maximizing the gliding distance. It's also notable tat the $C_m \times \alpha$ plot crosses 0 around the the same 8 deg, meaning the profile is generally trying to point at that angle.

From 8,

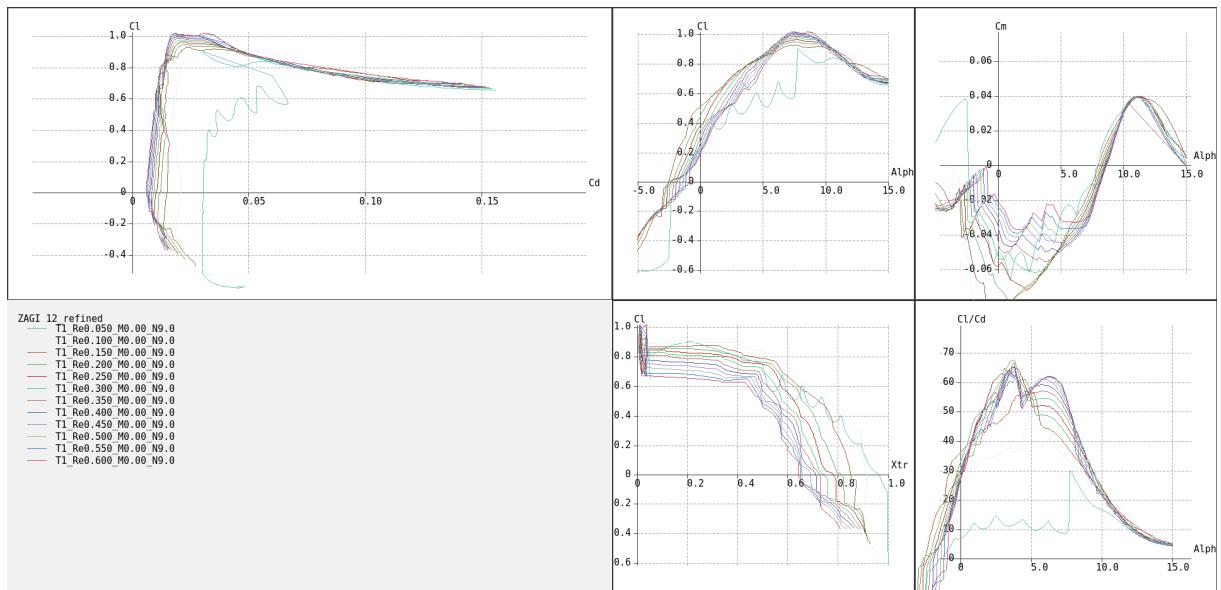


Figure 6 – Zagi 12 characteristics

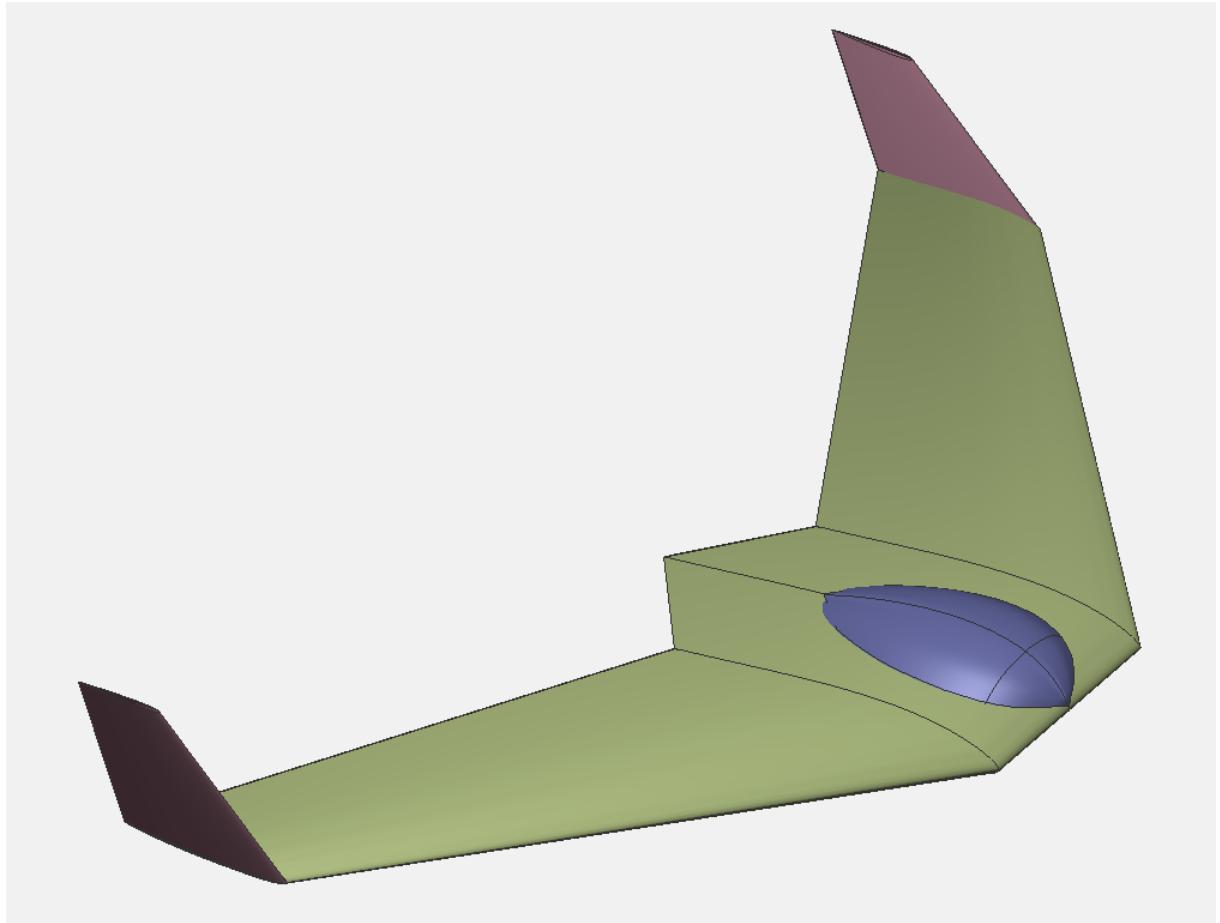


Figure 7 – First concept of the aircraft.

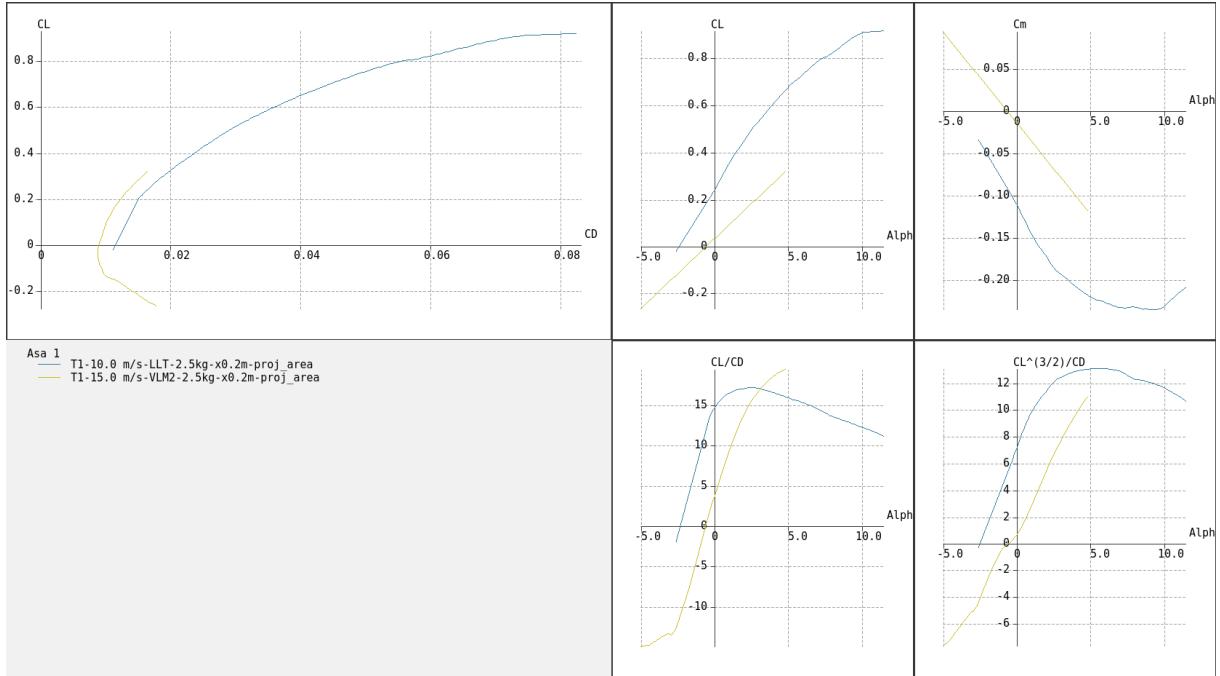


Figure 8 – Flight characteristics of the preliminary aircraft design.

3.5.2 Final Design

Due to building issues and the desire to maximize both effective payload and flight autonomy, the design was simplified, extending the chord back on the beginning of the wings, as seen on figures 9 - 11. The electronics bay was embedded into the main section, reducing the aerodynamical cross-section, thus reducing drag.

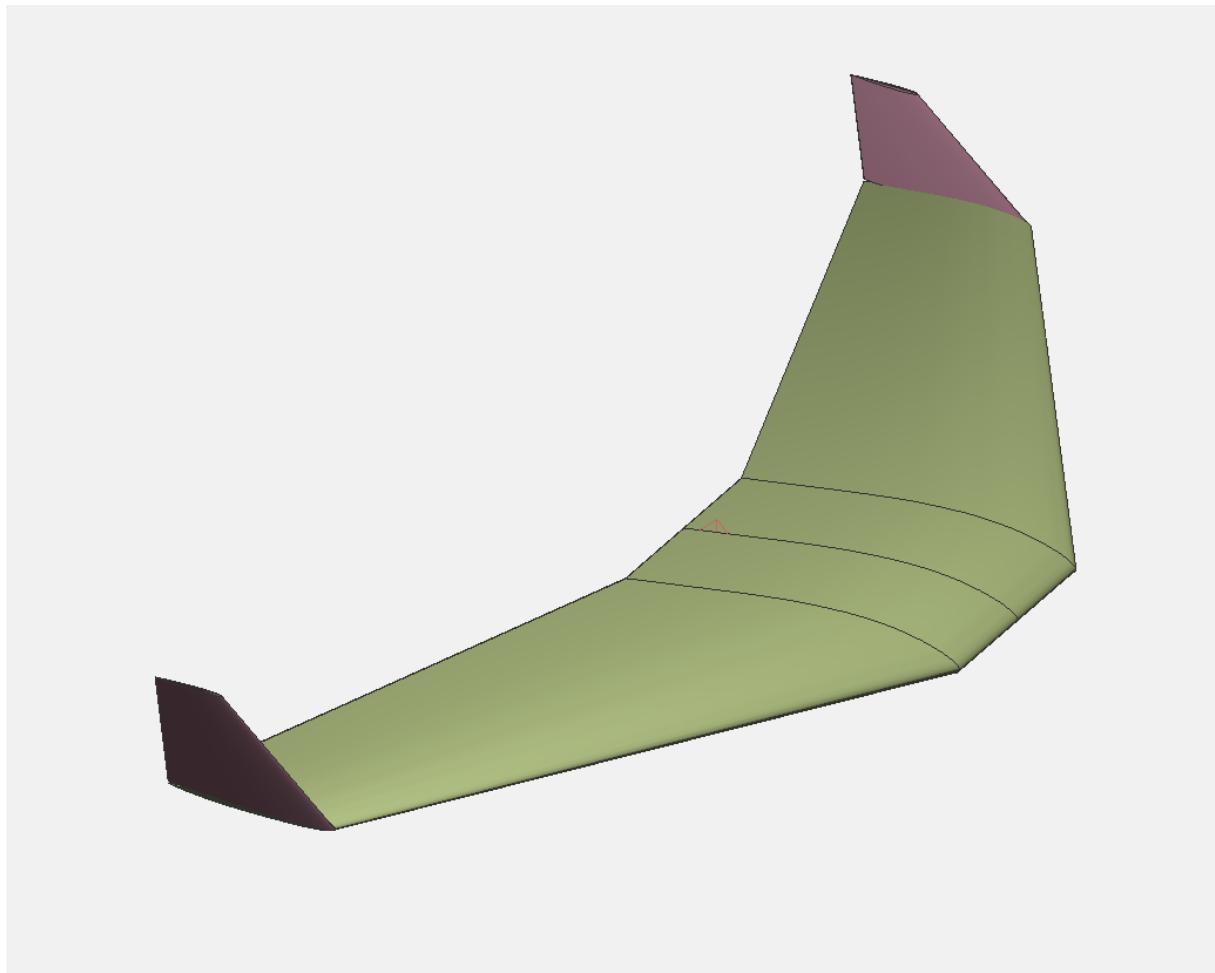


Figure 9 – Final design of the aircraft, on XFLR5.

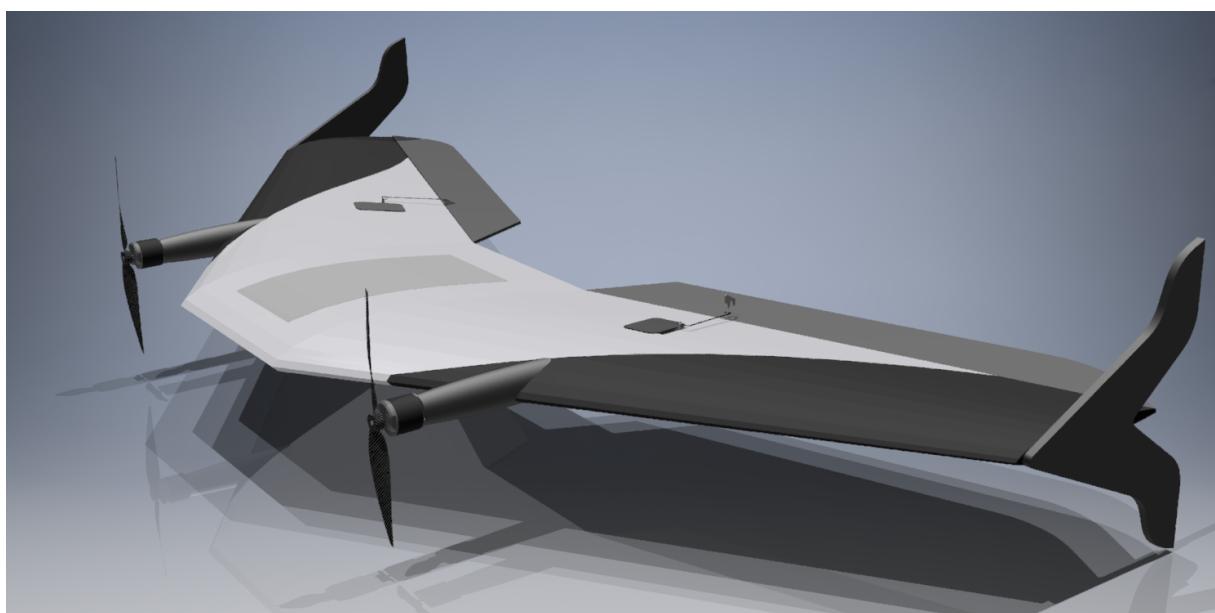


Figure 10 – Final design of the aircraft.

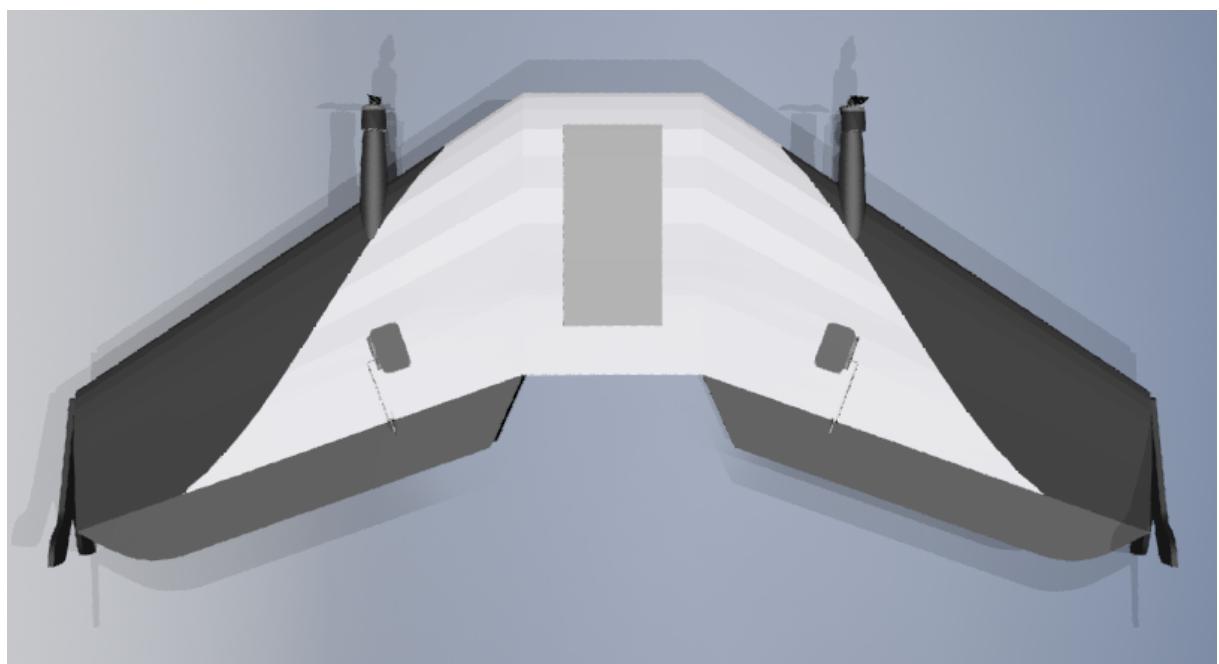


Figure 11 – Final design of the aircraft, top view.

4 The Eletronics

In order for the aircraft to fly and navigate autonomously, onboard electronics are required, for both actuation, power source, and navigation. Some of the used electronics was already available, and was chosen for this reason.

4.1 Propulsion

Due to the familiarity and availability, the Mikrokopter Mk3538 Motor was chosen, paired with E-Max Simon 60A escs.

Experimental curves for the motor are available at Mikrokopter's website, and the relevant ones are reproduced on Figure 12. Each motor should give, on 25 V, at least 2.2kg of static thrust when paired to 12 inches propellers, up to 3.4 kg on 15 inches, while drawing 34 A, or about 754 W.

4.2 Batteries

As each motor can draw up to 34 A, the battery should be able to provide up to 68 A without issues. The Batteries chosen are also the ones already in use by the company,

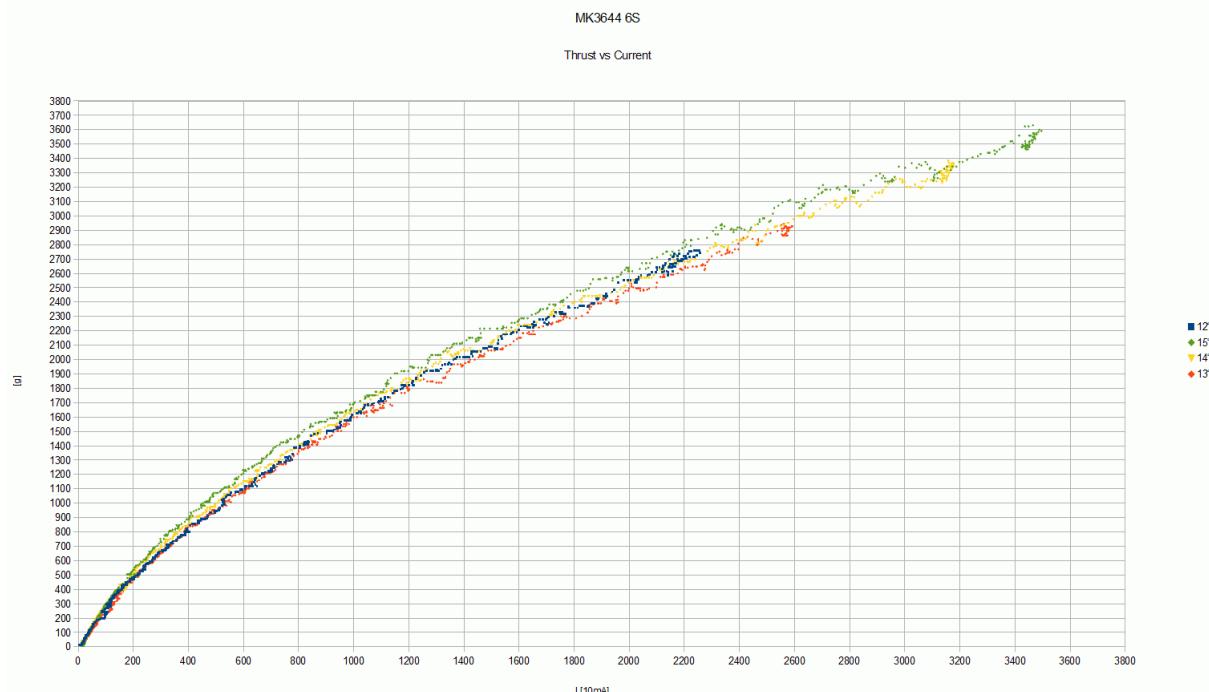


Figure 12 – First concept of the aircraft.

Vislero 4500 mAh 20C, which, at 20 C rating, are able to sustain a constant draw of up to 90 A.

Each weigh approximately 750 g and measures XXxYYxZZ mm.

4.3 The Control Surfaces

The control surfaces must be slightly larger than usual for a flying wing, as on a tail-sitter a reasonable amount of air must be deflected on hover situation, while on most wings a steady airflow is assumed. It's suggested to have control surfaces taking up to 30% of the chord of the wings. Since they are easily swappable, it was decided to start with smaller ones, and replace it if necessary

4.4 The Flight Controller

The multirotor had a huge boom last 10 years. In 2009 the first hobby-grade flight controller for multicopters was born, Rolf KaptainKuk Bakke's "KK board". Using a simple AVR controller and three gyroscopes, the board could control angular speed on three axis, enabling pilots to control the multirotors. It was programmed in AVR assembly and had individual PID controllers for each axis. Shortly after, Alexinparis noticed the gyros on the Wii Motion + controller, and MultiWii was born. This project grew to support a variety of sensors and boards, and had an active development community, but has now saturated the AVR controller's capability. Shortly after, still in 2010, DIY Drones released the open-source Arducopter, featuring more advanced flight modes, and even autonomous flight. It did still involve compiling code and flashing it to the controller though. In 2011, DJI started to get visibility with the NAZA controller, which showed remarkable stability, and later got upgraded with a GPS allowing the drone to return to home and hold position in the air. The controller was often sold with a

The Flight Controller is a PixHawk, running latest Beta release of ArduPlane, where there's experimental support for tail-sitters.

5 The Control Structure

The control Structure used is the one of ArduPlane, in hover, or tail-sitter mode, the ArduCopter stabilization system is used, while in airplane/fixed-wing mode, Arduplane's controllers are used. Both will be discussed and explained in the following sections.

5.1 On Airplane Mode

On Airplane mode, the aircraft is always moving forward, towards the X axis, position control depends on defining a route and pointing the aircraft in order to remain on it.

5.1.1 Roll and Pitch Control

The roll and pitch control loops (seen on Figure 13) are responsible for keeping the aircraft on the desired orientations on the X and Y axis. Usually, roll is controlled by turning the elevator up and down, while roll is controlled by the deflecting the ailerons. On this aircraft, however, there are only two control surfaces, such that the output of both controllers are summed (mixed, and is usually used in the RC world) in order to control both axis at the same time. While at first they look like a classical P+I+D controller, there are some small changes:

- There's a feedforward controller trying to cancel the current angular rate $\dot{\phi}$
- The Derivative and Integral terms are scaled to the airspeed, and the controller's output as well. This is because as the aircraft moves faster, less deflections are necessary for the same movement of the body.

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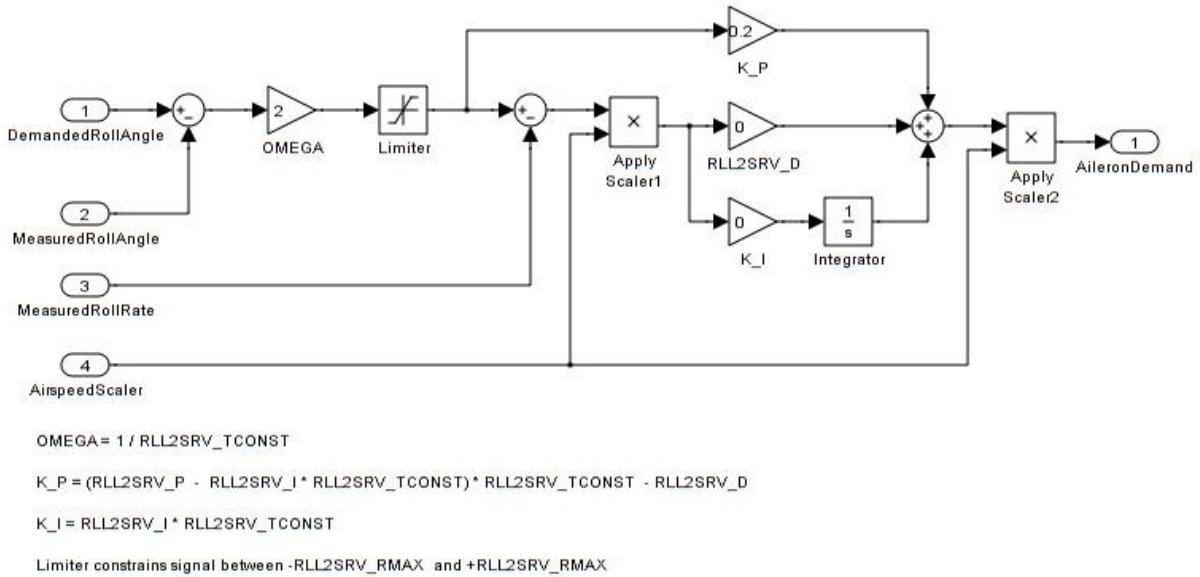


Figure 13 – Roll control loop.

5.1.2 Yaw Control

The Yaw Control loop controls the angle around the Z axis, ψ . This is usually used for landing only, and is not used on this aircraft on airplane mode. It can, however, be seen on Figure 14. Like the D and I terms on the roll axis, the controller's output is again scaled with the square of the *AirspeedScaler* factor. difuq

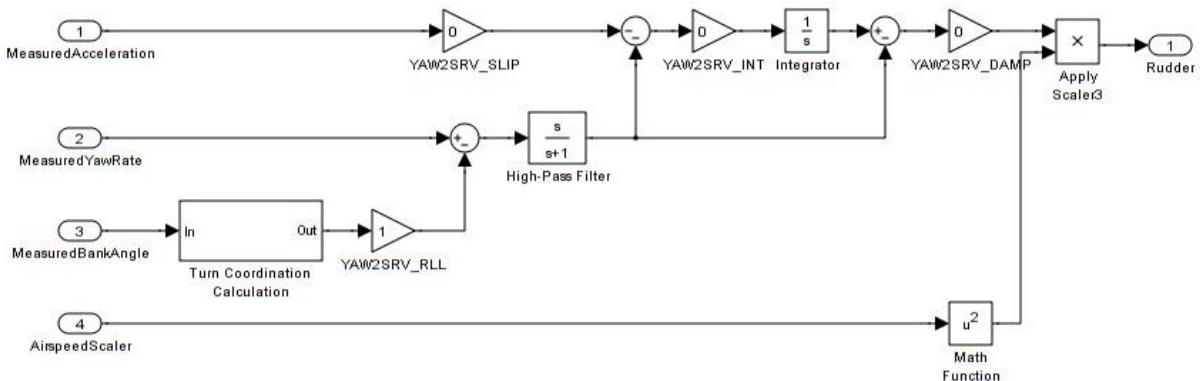


Figure 14 – Yaw control loop.

5.1.3 Navigation: L1 Controller

Since a fixed-wing aircraft usually can't fly in-place, waypoints can be used in two general ways, the aircraft can fly around it in circles, or hit it and then follow to the next one.

In order to circle it, a PD controller is used with a feed-forward centripetal force.

6 Prototyping

As in any product development, a few prototypes were developed. First a smaller , 50cm wingspan aircraft with no airfoil was assembled to test and tune the flight controllers. The reduced version also enabled testing in close spaces and proximity with people with reduced danger.

With the reduced prototype proven, the larger one, photography-ready was developed. The larger one is closer to the final desired product, and is able to be used as such.

Both prototypes are described, as well as their assemblies, in the next sections.

6.1 Reduced Scale Prototype

A reduced prototype was used for preliminary tests of the flight controller and control systems.

Mechanically, this prototype consists of a foam board, two motors, and two control surfaces.

Smaller electronics are used as well. The servos are Turnigy 9 gram servos, The motors are AXN Floater-Jet 2208 2150KV brushless motors, the Escs are HobbyKing's RedBrick 30A ESCs, and the battery a Zippy Compact 3s 1000mah 35C.

The control surfaces were taped to the main body, and linked to the servos by a wire and plastic horn.

The motors had a custom mount 3D-Printed and fitted into the foam.

For the tests and tuning, the prototype had a hook on top, so it could be hang on the ceiling to avoid hitting the floor and walls during the tests.

The first prototype and It's components can be seen on Figure ??

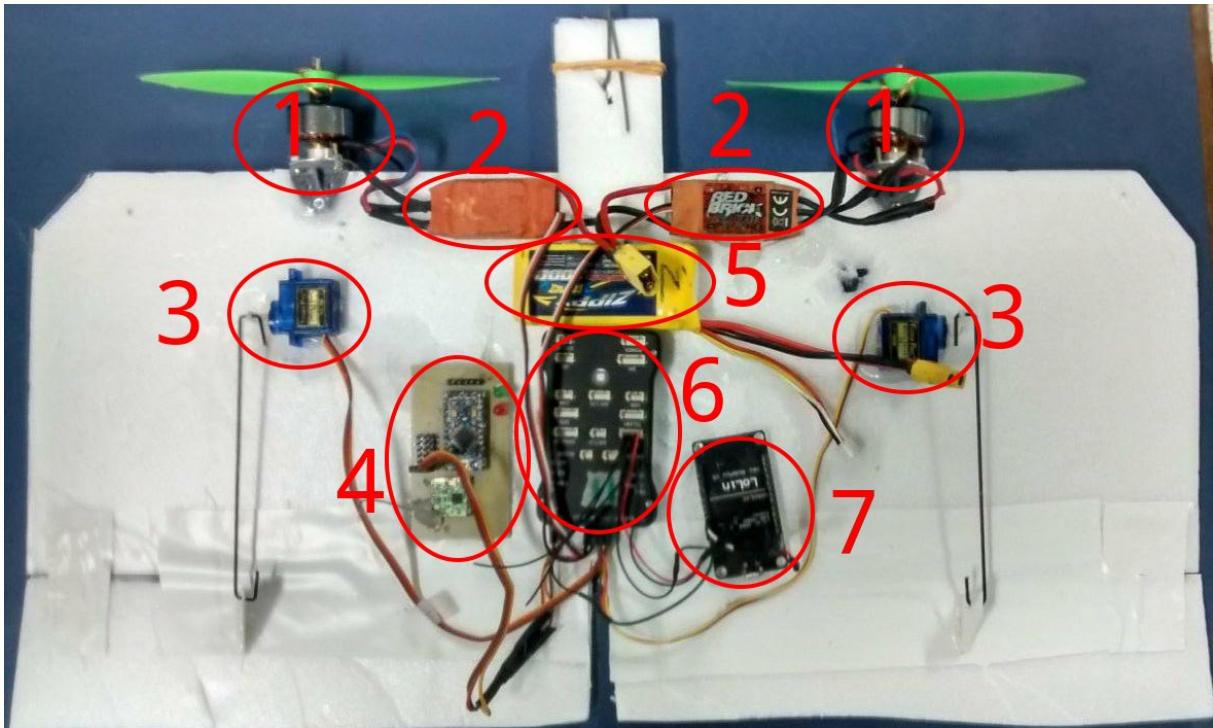


Figure 15 – Reduced Prototype and parts:

- 1 - Motors and 3D-printed mounts
- 2 - HobbyKing RedBrick 30A ESCs
- 3 - Turnigy Pro 9 gram servos
- 4 - Diy OpenLRS 433 MHz receiver
- 5 - Zippy Compact 3s 1000mAh 35C lithium-polymer battery
- 6 - Pixhawk controller
- 7 - ESP-8266 board for telemetry

6.2 Large Prototype

For the larger prototype, standard RC building and fast prototyping technologies were used. The Zag12 airfoil at root was 3D printed in 3 parts (Figure ??) then joined and insulated from the hot-wire heat with aluminum foil. For the trapezoidal wings, one side of the wire was tied to a fixed point, in such way that, if the airfoil was a circle, the wire would cut a cone on the foam. This enabled the cut of the trapezoidal wings out of foam. For the center section, two profiles were 3D-printed. their perimeters were then marked with numbers, in such way that two people, one on each side, could coordinate the hot-wire cutting process.



Figure 16 – 3D Printed Airfoil

This process isn't perfect for the trailing edge, so some of it needs to be removed, which later gets replaced by the elevons.

The cut foam then needs to be sanded down to remove imperfections. The half-wings are then joined with hot glue, and fiber glass spars are used to reinforce the structure.

From this point, The sections can be joined permanently or spars can be used to quickly assemble them.

With the three sections properly cut, they are glued together and sanded, and glass fiber rods were embedded and glued into the structure, two on the top and two on the bottom.

With the main structure assembled, the servos were embedded into the structure. A pocket was carved with hot wire, and two nut-holding 3D-printed parts were embedded deep into the foam and used to screw the top cover, as seem on the figure 17.

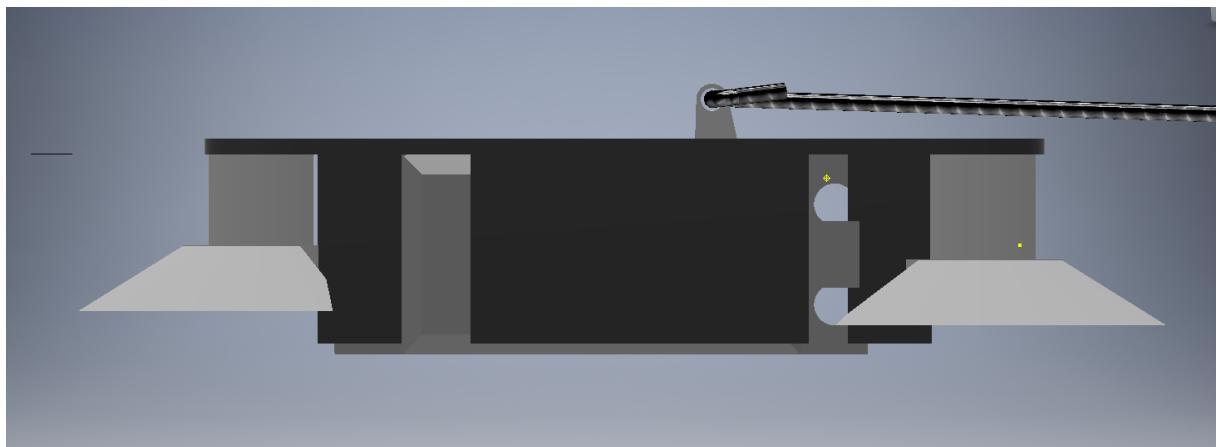


Figure 17 – 3D-printed servo mount structure.

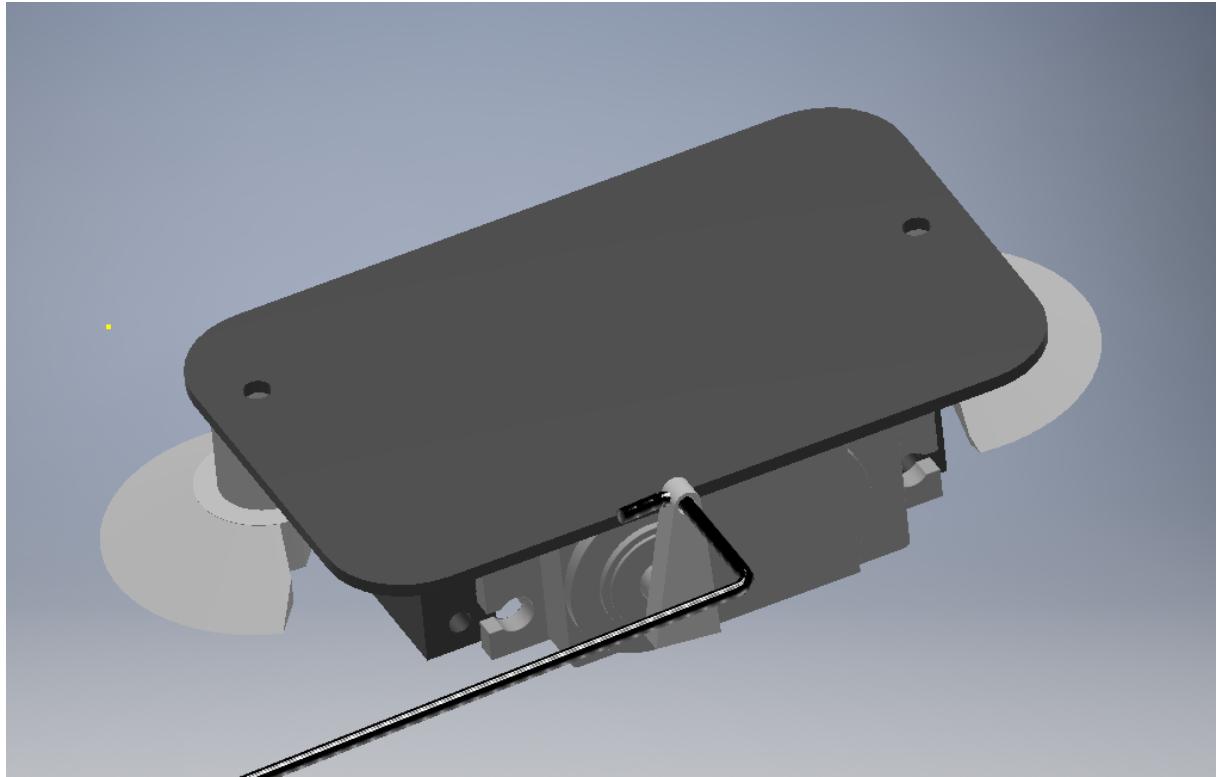


Figure 18 – 3D-printed servo mount structure.

The main structure was then covered in vinyl, for aesthetical and structural purposes (the tension on the vinyl helps making the structure stiffer). The vinyl is a material that shrinks when heated, which makes it tension itself over it's surface.

The motor mounts were designed so they fit perfectly on the wing profile, and 3D-printed, glued and screwed into the main wing. The mounts can be seen on figure 19

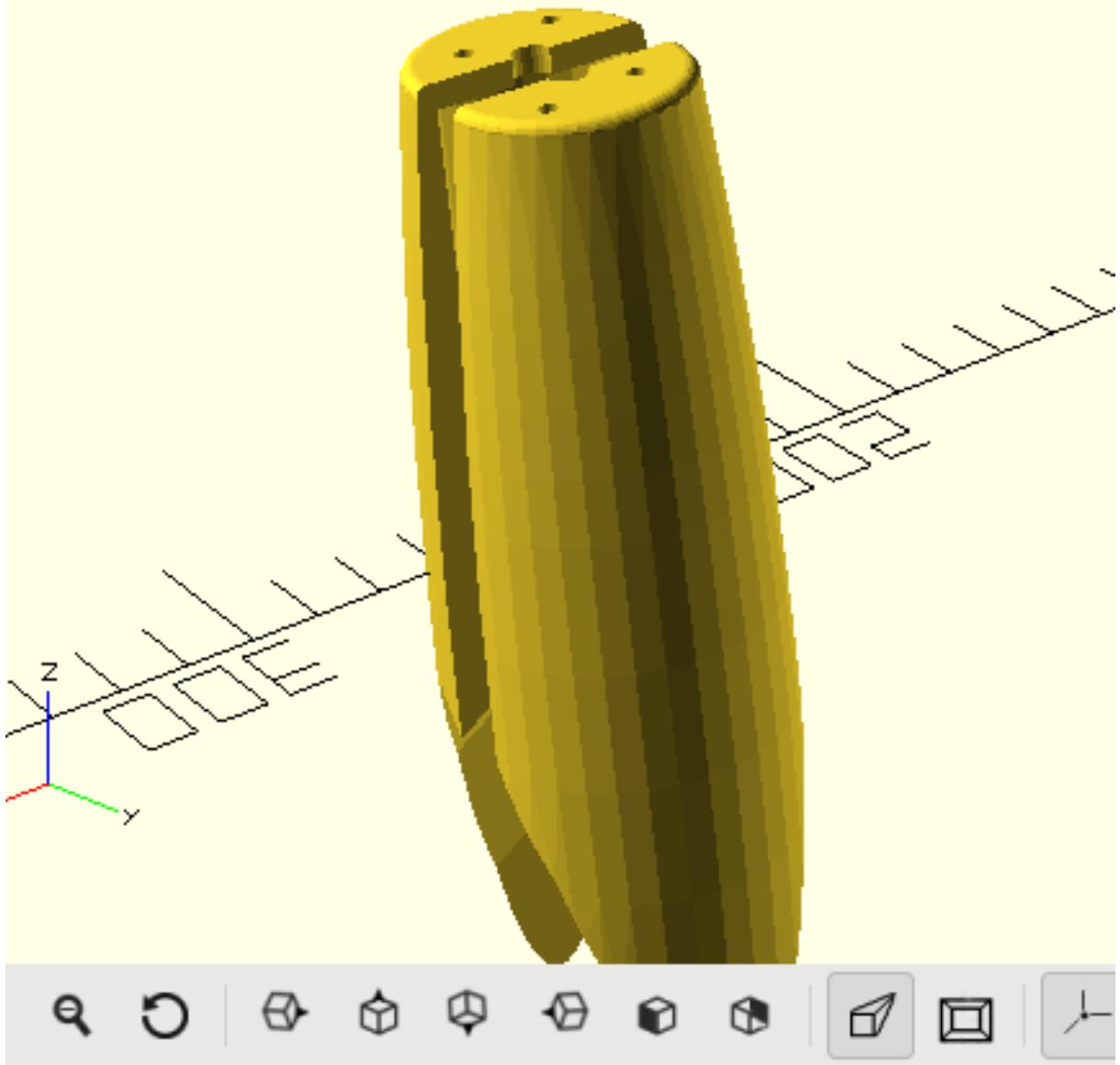


Figure 19 – 3D-printed motor mount structure.

The electronics bay was cut using hotwire and carved with a knife. A hot air blower was used to finish the inner surface. The components were placed keeping in mind flexibility to change the camera and batteries without affecting the center of gravity too much, maintaining the approximately the same flight characteristics.

The flight controller was glued with vibration-dampening material. The battery was attached with velcro, and the remaining components are either glued or screwed in place. Special care was taken into keeping the magnetometers away from the motor and battery wires, as the induced magnetic field can adversely affect the magnetic readings.

The hinges were made using a type of fibrous tape. The tape was cut into pieces and glued onto itself, in such way that the piece of tape first sticks on the top section, then on the overlapping sections does not stick at all, and finally, sticks on the bottom. Then these compound tapes are glued in pairs, with one piece sticking on the bottom of the wing and top of the elevon, and the other on the top of the wing and bottom of the elevon. This can be seen on Figure 20.



Figure 20 – hinges setup.

The winglets, which usually have only an aerodynamic function, as they increase the yaw (Z) stability and help avoid wing tip vortices, here also need to work as a landing gear in VTOL mode.

As they need to let go after certain amount of force is exerted, and need to be removable to aid in transportation, a magnetic system was idealized. On the wingtip there's a 3D-printed profile with slots for the magnets, and the mirrored profile is also present on the winglet. This profile can be seen on Figure 21. This profile made sure that four pairs of magnets touch on each winglet. However this design allows slipping between the airfoils, so Velcro was used again to help stiffen the structure, without making it too hard, allowing the winglet to absorb impacts and come loose before damaging the rest of the aircraft.

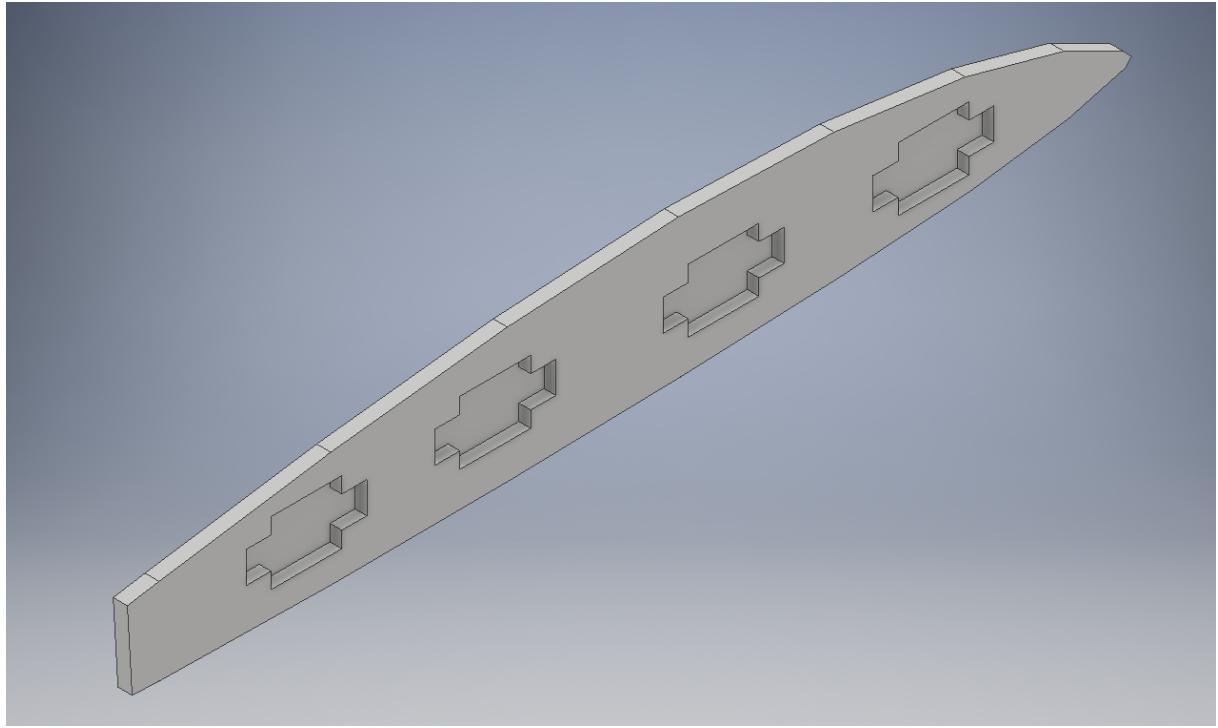


Figure 21 – 3D-printed magnetic coupler.

7 Assessment

The assessment was incremental. First, the aerodynamic properties were tested on a manual flight, qualitatively, regarding properties such as stall angle, stall speed, and equilibrium point in flight. Following this, the hover capabilities were tested, such as altitude and attitude control. With the basic flight capabilities proven, a few autonomous, test flights were performed, without VTOL. Finally, its VTOL capabilities were benchmarked. These tests are better described, as well as their results, in the following sections.

8 Conclusions

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