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7th DOCUMENT ANNEX V: 3D PRINTED WING DEVELOPMENT

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3 NOMENCLATURE

UAV	Unmanned Air Vehicle
RMS	Rapid Manufacturing System
CAD	Computer-aided Design
CNC	Computer Numeric Control
STL	STereoLithography file format
PLA	PolyLactic Acid

4 INTRODUCTION

This document shows the process from the basic design to the ready to flight wing. Designing process starts with the Multiplex Easy Star basic model and develops an easy and powerful methodology to obtain the stereolithographic file required for the manufacturing stage.

Manufacturing process has developed an iteration method to reduce wing weight. 3D printed wing mechanical properties have been tested.

Assembly process has used a heat welding system for parts union.

Result has been evaluated in an ultimate load static test and a wing flight test.

5 BASIC MODEL

The aim of the study is the manufacturing process, and then the effort has been focused on it and requires starting with a selection of a real model to avoid previous engineering design stages effort. At the same time, a real model reference will allow the final comparative results in order to evaluate the feasibility of the RMS. The requirements for the beginning point model have been:

- Excellent CATUAV applications support.
- Easy assembly and shipping.
- Standard aero model dimensions.
- Commercial success.
- Low Cost model.

The only alternative for all those requirements is the MULTIPLEX Easy Star, produced by MULTIPLEX[1]. Jordi Santacana, CATUAV Director, justifies the excellent application. The easy assembly and shipping is the best feature of this model because it is composed by only 4 pieces: wings, fuselage and horizontal stabilizer [1]. Dimensions are a normal statistic distribution for most significant models range, with a wingspan of 1370mm. Commercial success is displayed by the lifetime, the continues new versions and the Chinese copied model, called BITXLER [2]. Finally low cost requirement is justified by the German version cost: 70.90 €, or the Chinese one: 50.46 €. (Prices obtained by companies' website and March 9 2014 US Dollar conversion value).

MULTIPLEX Easy Star is a ready-made aircraft made of ELAPOR®, a high-tech particle foam, a useful material for moulded foam model airplanes. ELAPOR® models share the following features:

- Extremely robust.
- Capable of withstanding enormous loads (airspeeds around 200 km/h)
- Stable in form over a wide range of temperatures.

[1] MULTIPLEX is a German developer and producer of radio control systems for model sport applications. For more interest, see: http://www.multiplex-rc.de/en/home.html

- Accurately moulded, incorporating fine detail features (accurately-fitting internal parts), and when an accident occurs, they are simple and quick to repair using cyano.

Besides the main material, injection-moulded plastic parts are used for areas of the model such as motor installation and fuselage / wing connections. The overall result is an assembly: flight time ratio with an excellent flight performance.

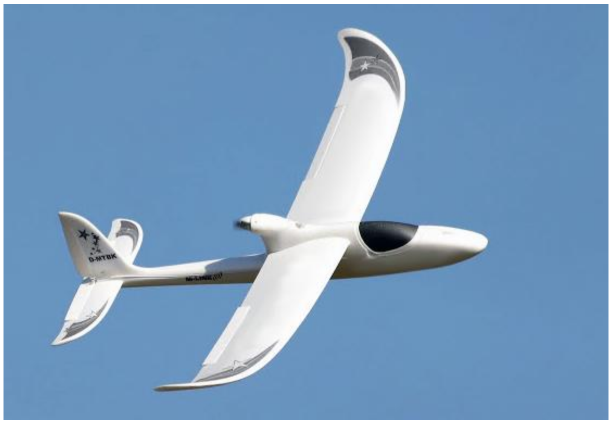

Figure 1 MULTIPLEX Easy Star flight operation [1]

5.1 Features

MULTIPLEX Easy Star, see Figure 1, is a radio controlled, electric powered and foam constructed Model Kit for Intermediate Modeler/Fliers. The main features are:

- Construction: Elapor foam on the fuselage, wing and tail section.
- Wings: Two-piece, foam construction, white in color, optional ailerons.
- Radio Compartment: Foam, allows high capacity LiPo packs.
- Landing Gear: No landing gear, model lands on its belly.
- Hardware: Pushrods and other hardware included.
- Spinner: White plastic 1.4" (35mm).
- Propeller: Plastic, folding pusher type, pro faces the rear of the airplane.
- Decals: Precut colorful Easy Star II logo decals (removed from Figure 1)

The assembled pack includes: foam fuselage, wings, tail section, prop, spinner, decals, instruction manual and hardware. And requires radio, servos, motor and battery.

5.2 Specifications

Wingspan:	1370mm
Wing Area:	2810 dm^2
Wing Loading:	25.27 g/dm^2
Weight:	709 g
Length:	978mm
Airfoil:	Flat bottom, high wing configuration
Center of Gravity:	78mm back from the wing's leading edge at the fuselage sides
Control Throws-Elevator:	5mm up,4mm down
Rudder:	Right & Left: 10mm

Table 1 MULTIPLEX Easy Star specifications [1]

5.3 COPYRIGHT

The author of this work have been sensible to author rights by sending a Permission Document to Multiplex Company in order to explain the interest of this study in the Multiplex Easy Star model design for being manufactured in 3d Printing technology and buying a unit for testing and knowhow.

6 DESIGN TOOLS

6.1 Software

Once the basic model to develop a UAV 3D printing technology has been selected, the design phase begins. The requirements for the Computer Aided Drawing (CAD) design software have been:

- Airfoil data [txt] files compatibility.
- Intermediate and Expert designers use.
- Powerful software.
- Support STL files exportation.
- Transversal sectors utility.

6.1.1 Open-source software

Open-source software alternatives that meet previous requirements and have been used for this study are:

- 3dtin[2]
- Sketchup[3]
- OpenSCAD[4]
- Wings3D[5]
- Blender 2.69[6]

6.1.2 Closed-source software

Closed-source software alternatives that meet previous requirements and have been used for this study are:

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[2] *3dtin is an online OPENSOURCE CAD software developed by LAGOA. http://www.3dtin.com/*

[3] *Sketchup is an OPENSOURCE CAD software developed by worldwide designers. http://www.sketchup.com/es*

[4] *OpenSCAD is a software for creating solid 3D CAD models. Free Software released under the General Public License version 2. http://www.openscad.org/index.html*

[5] *Wings3D Winged Edge Data Structure (WEDS) is an OPENSOURCE subdivision modeler. http://www.wings3d.com/*

[6] *Blender is a free and open source 3D animation suite. http://www.blender.org/*

- Autodesk[7]: AutoCAD 2012 & Inventor Professional 2014
- Dassault Systèmes[8]: SolidWorks 2013

Closed-source software have been used under student licenses:

- Autodesk AutoCAD 2012 - standalone type - product key: 001D1
- Autodesk Inventor Pro 2014 – standalone type – product key: 797F1
- Dassault Systèmes SolidWorks 2013 – ETSEIAT University License

Image Software:

- Adobe[9] Photoshop CS6, under trial version

6.2 Camera

The camera used to take the photos has been a CANON EOS 550D with a 24-105mm ZOOM lens.

6.3 Measurements

The measurements tools have been:

- Ratio 5m tape measure. Precision: ± 0.5 mm
- Ratio caliper. Precision ± 50 μm
- Up to 3Kg Scale. Precision ± 0.5g

Statistic methodology for measurements have been approximated by a T Student probability law between 7 measurements [3].

Validation used methodology have been a digital photo projection into the CAD software.

[7] Autodesk is a USA Company world leader in 3D design, engineering, and entertainment software and services. http://www.autodesk.com/

[8] Dassault Systèmes is the Company's world-leading 3D software applications to design, produce, and support. http://www.3ds.com/

[9] Adobe Systems Incorporated is a USA software Company. http://www.adobe.com/

7 CAD DESIGN

The CAD Design phases have been divided in the main pieces of the model:

- Wing (developed in this document)
- Fuselage
- Tail

7.1 WING Design

The Multiplex Easy Star wing is a 2 pieces element, left and right part, made of Moulded Elapor foam and joined with a GFR tube, a hybrid wing. 3D printed wing design has adopted the same system. Since wings are symmetric, wing design process have digitalized right wing, see Figure 2, and the other will be generated automatically by symmetric transformation.

Figure 2: MULTIPLEX EASY STAR right wing [1]

The first measurement has been the root airfoil, which is inserted to the fuselage, see Figure 3. Section shows the GFR tube perforation and, at the middle bottom, the grommet cable for connecting the aileron servo. Tail edge has a non-usual thickness which is an ELAPOR manufacturing requirement. Designed tail edge thickness could be improved since RepRapBCN allows 0.4 mm layers.

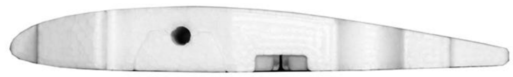

Figure 3: Root Airfoil.

The same airfoil aspect ratio of the 2D image axis has been validated by measuring an as large as possible dimension in any axis. Chord for the X Body Axis measurement, C=201.5 mm and thickens in the circular perforation point for the Z Body Axis, T= 26.6 mm. The image has been scaled according to the C value obtaining a T'=25.9, aspect ratio for Z axis has been calculated in next equation:

$$Image\ Aspect\ Ratio\ Z = \frac{T}{T'} = 37/38 = 0.974 \qquad (I)$$

The digitalized airfoil has been analyzed in a 4 digits NACA nomenclature in order to specify main features. Result is a NACA 2412 for the first approximation. First digit is the maximum camber % = 2. Second digit is the maximum camber position = 45%. Last digits are maximum thickness % = 12.

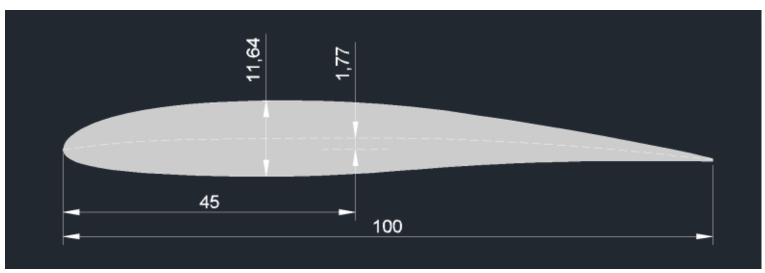

Figure 4: Computed airfoil

UAV conditions have a low Reynolds operation flight. Aerodynamic study is not the aim of this project; thereby this study has used a software developed in previous projects, Albatross UAV, in order to obtain a high aerodynamic performance for 120m level flight, the new limit flight according to AESA[10].

[10] *AESA. Agencia Estatal de Seguridad Aérea.*

http://www.seguridadaerea.gob.es/media/4229776/el_uso_de_los_drones.pdf

Result, see Figure 4, has been a 400 points DATA file that allows starting the wing design.

Wing dimensions have been 1500mm wingspan and 200 mm root-chord. Similar dimensioned to the STATE OF THE ART references and the Easy Star aeromodel.

Parameter	Symbol	Value
Wing area	S_W	25.2 dm2
Wing position		High wing
Airfoil (similar)		NACA 2412
Aspect ratio	AR	8.93
Taper ratio	λ	0.3
Tip chord	C_t	0.6dm
Root chord	C_r	2dm
Mean Chord	MAC	1.68dm
Span	b	15dm
Twist angle	α_t	2.75º
Sweep angle	Λ	7º
Dihedral angle	Γ	2º
Incidence angle	i_w	3º

Table 2: Wing parameters

7.2 Structure

The wing has been designed as a composed body since it has various requirements. The main loads over the wing are aerodynamic loads, where lift is the highest, leading and trailing edge loads and static pressure loads [4]. The wing elements have been the skin and the core.

According to low Reynolds applications: sailplanes and wind turbines airfoils, there are three alternatives that satisfy the constraints [5]: monocoque (A), ribs and spars (B) or foam core (C). See Figure 5.

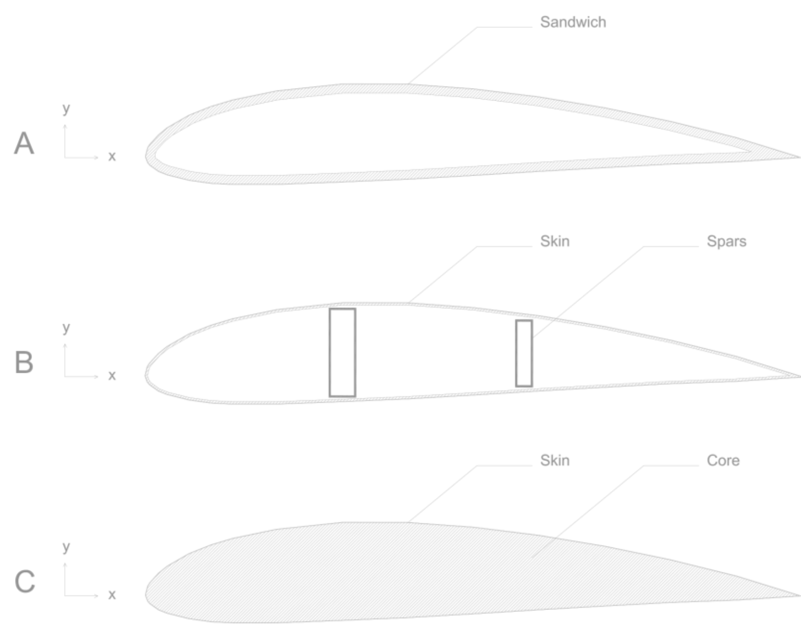

Figure 5: Wing structure alternatives

The skin supports the aerodynamic loads and transfers them to the ribs. The down skin is designed for maximum strength, toughness and fatigue. The upper skin is designed to support compression loads and buckling issues. The skin is an important factor of the total wing and UAV weight.

The stability increases with the thickness of the sandwich skin. The core can be fully air, composed by spars or fully lightweight foam. In the case of spars, these elements support the main structural state, the bending moment created by lift loads. In the case of ribs, these elements mold the shape of the airfoil, connect the spars, and support compression and torsion loads.

The requirements to compare these three solutions have been:

- Weight, because it must be the lowest possible.
- Inside free space, to allow space for avionics.
- Setting-up, to make the manufacturing process and assembly easier.
- Reliability, to endure the correct flight operations.

3D printing technology has been able to print perimeters, ribs and spars in the testing stage, but foam core alternative requires a post process of injection.

The normalization of the alternatives for the PRESS rating method has been based on next hypothesis:

- Ribs and spars have best weight performances than monocoque because it requires more perimeter thickness to support the same loads and torque.
- Monocoque has the best performance in free space.
- Monocoque has the best performance in setting-up factor because G-Code parameters are only perimeters.
- Foam core has the best performance in reliability because is the most steady in fatigue requirement.

Rating	Weight	Free space	Setting-up	Reliability
Factor	4	2	1	2
Relative (Pj)	0.44	0.22	0.11	0.22
Alternatives				
Monocoque	2.00	3.00	3.00	1.00
Ribs and spars	3.00	2.00	2.00	2.00
Foam core	1.00	1.00	1.00	3.00

Table 3: Wing structure scores table

	Weight	Free space	Setting-up	Reliability
Monocoque	0.889	0.667	0.333	0.222
Ribs and spars	1.333	0.444	0.222	0.444
Foam core	0.444	0.222	0.111	0.667

Table 4: Wing structure appreciation matrix

	Weight	Free space	Setting-up	Reliability
Monocoque	0.00	0.33	1.11	1.44
Ribs and spars	0.67	0.00	1.22	1.89
Foam core	0.44	0.22	0.00	0.67
	1.11	0.56	2.33	

Table 5: Wing structure domination matrix

Monocoque	1.30
Ribs and spars	3.40
Foam core	0.29

Table 6: Wing structure selection result

Selected wing structure has been the ribs and spars system, see Table 6. 3D printing technology is able to print internal structure by CAD design or Infill strategy. CAD designed structure has been a difficult process and large in time that sometimes it is not able to be computed. Infill strategy is a rapid strategy with less than 3 iterations to adjust the designed structure. Therefore this project has 3D printed wing parts by Infill iteration method to adjust wing design specifications.

Wing parts supports the maximum loads and torque at the union between wing and fuselage. Moving towards the wing tip, there is a distance where the skin is able to withstand the loads itself. From this distance monocoque would be able to support structural requirements without spars, but testing stage has justified that the minimum perimeter is 600 μm thickness, not enough to ensure aerodynamic airfoil shape. Therefore Infill has been used inside all the wing parts.

8 1st WING MANUFACTURING TEST

The aim of this topic is to print a wing. As we have seen in UAV Design Annex, basic design is a 1500 mm wingspan, 200 mm root chord, 30% nonlinear taper ratio and winglet tip; see Figure 6. As we have seen in the 3D Printer Annex, printing size of REPRAP BCN 3D+ is 24 x 21 x 20 cm in the X-Y-Z axis. These factors should be broken wing by parts to be manufactured.

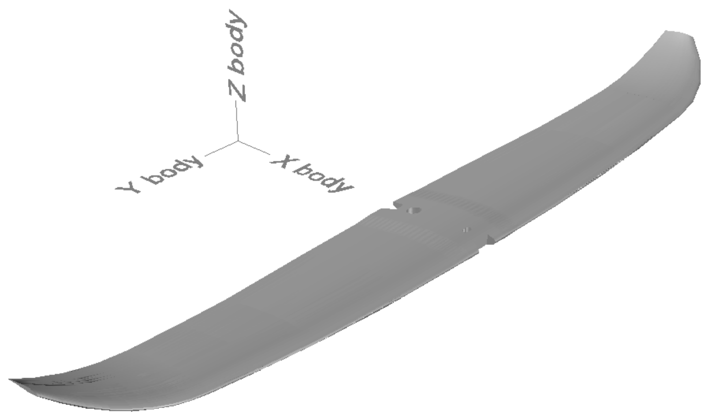

Figure 6: Wing design

The aerodynamic requirements have modified the body axes relative to the printer axis. The reason is the roughness of the surface layered where the lines must be aligned with the airstream. The volume requirements have been met with a division into parts of the wing. See Figure 7.

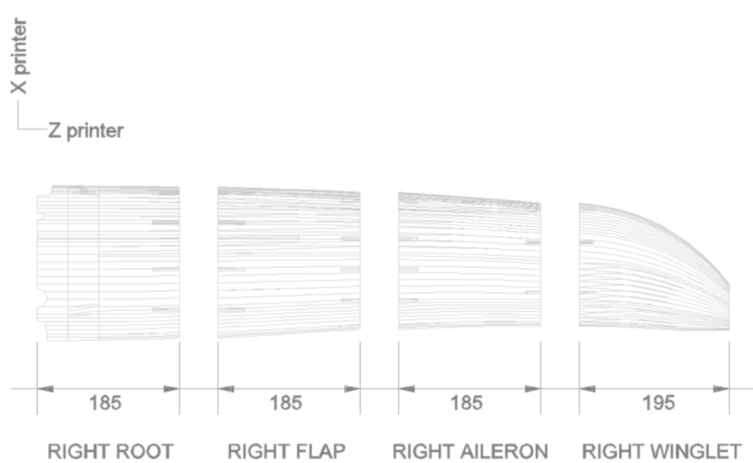

Figure 7: Wing 3D printing parts

8.1 WINGLET WING PART

The first test of the tip part of the wing, called Winglet, gets previous test skills and introduce a Z axis curved part printing test. Provided union has been developed from I form to double circular tubes in the extremes in order to optimize the strength-weight ratio while supporting required torque.

8.1.1 Winglet CAD design

The basic Multiplex Easy Start winglet have been digitalized by photographic measurements method. Designing CAD element have not been able to make an approximation of X and Y shape to a parabolic equation and the z aspect ratio by a similar equation, instead a cross sections method have been able to shape the winglet.

Cross sections method have used four offset sections, see Figure 8, digitalized by the original shape and the LOFT command creates a 3D solid by specified series of cross sections. The cross sections define the shape of the resulting solid.

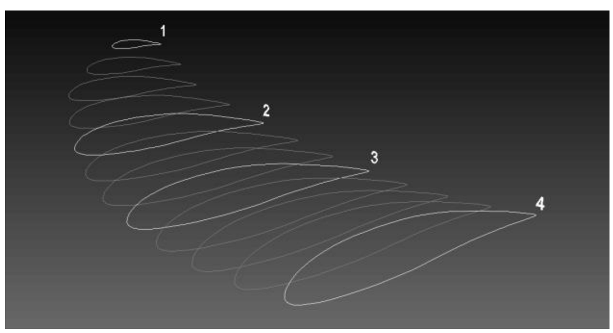

Figure 8: Winglet part CAD. Loft cross sections

Winglet part is 195 mm Z printer axis length, 160 mm 4th section chord, 40 mm 1st section chord and 0.4 taper ratio, nonlinear path.

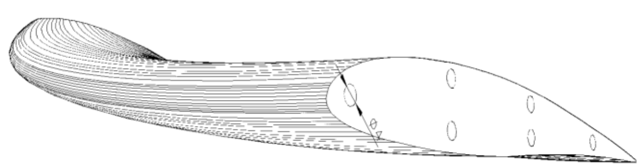

Figure 9: Solid CAD winglet part

Connectors are 4 mm diameter and 25 mm length holes ready to fix supported 3D printer or composites 3 mm tubes. The leading and trailing edge connector supports drag bending stress and two middle couples supports the lift bending stress and shear.

8.1.2 Winglet STL

High precision STL file, winglet 1, is 182 KB and creation time is less not a significant value. Table 7 shows the main properties of the created element.

Volume:	263.1838 cm³	Area:	553.8010 cm²
Points:	1862	Edges:	5580
Triangles:	3720	Shells:	1
Holes:	0	Bad edges:	0
Boundary edges:	0	Boundary Length:	0.00 mm
Flipped triangles:	0		
Surface is closed:			Yes
Surface is orientable:			Yes

	Min:	Max:	Ø:	Dev:
Edges/Point	4.00	15.00	5.99	0.73
Triangles/Edge	2.00	2.00	2.00	0.00
Triangle Quality	0.00	0.80	0.20	0.16
Edge Length	0.11	116.13	11.72	8.51

Table 7: Winglet part STL file information

This model has a Z axis variation, it will move the center of gravity to an unstable position, and therefore the base fixation must ensure bending stress during the printing process. First printing try will be naked, without extra supports, since previous tests justification.

8.1.3 Winglet G_CODE

The winglet G_CODE parameters (see Table 8) has been adjusted to reduce the strength/weight ratio and to improve the total printing time. Key commands have been perimeters and top-bottom solid layers.

Part	Winglet 1
Date	01/04/2014
Software	Slic3e 9.10b
Layer height	0,25
Perimeters	1
Top solid layers	2
Bottom solid layers	1
Fill density	0,04
Perimeter speed	90
Infill speed	60
Travel speed	200
Nozzle diameter	0,4
Filament diameter	2,92
Extrusion multiplier	1,1
Perimeters extrusion width	0,53 mm
Infill extrusion width	0,53 mm
Solid infill extrusion width	0,5 mm
Top infill extrusion width	0,3 mm
First layer extrusion width	0,39 mm

Table 8: Winglet1 G-CODE parameters

The G-CODE generated is a 3 minutes and 48 seconds process to write 191.469 lines of code. It is slower than previous test because of the 200 mm Z axis length, the maximum of the printer, see Table 9. Relative cost is 0.05 €/cm^3 (justified in the 3D printer Annex)

WINGLET 1	
Printing time	5h 2m 43s
Filament used	6302,3mm
Material volume	42,2 cm^3
Part volume	263,2 cm^3
Specific material volume	0,161
Cost	2,11 €

Table 9: Winglet 1 G-CODE features

Key feature of this element is the specific PLA volume of only 16%, compared with the beginning tests where the specific volume was over 20%. Total weight estimation has not been calculated, because there is no information about de used filament density, near 1.25 gr/cm^3 for supplied PLA, therefor it will be measured after printing stage.

Before printing the part is useful to check the extruder path. Repetier-Host software allows to graphically reading the generated G-CODE.

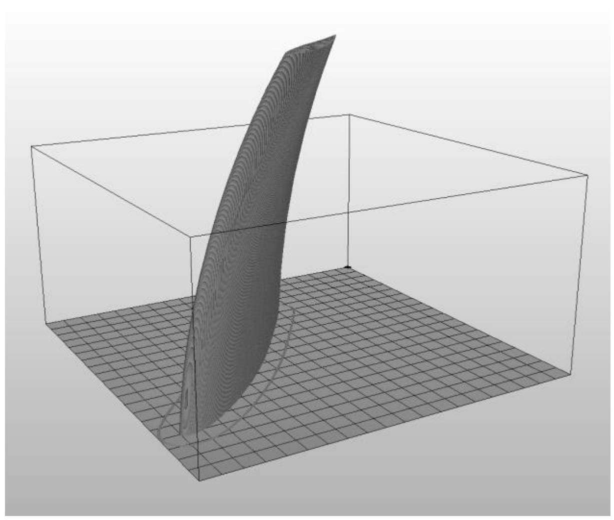

Figure 10: Winglet G-CODE simulation

Figure 10, demonstrates the difficulty of Winglet part stability during 3D printing process. Right base fixations must be improved by 3D printing specific lacquer. This testing study has used 3DLAC from Belloch laboratories S.A.

G-CODE check demonstrates that Winglet part has been optimized to improve the minimum used filament while supporting structural requirements. Figure 11 is a graphic simulation of the 3D printing path during 12 layers. The 250 μm layer height parameter, see Table 8, means that layer 70 is the +17.5 mm Z axis and layer 82 is the +20.5mm Z axis.

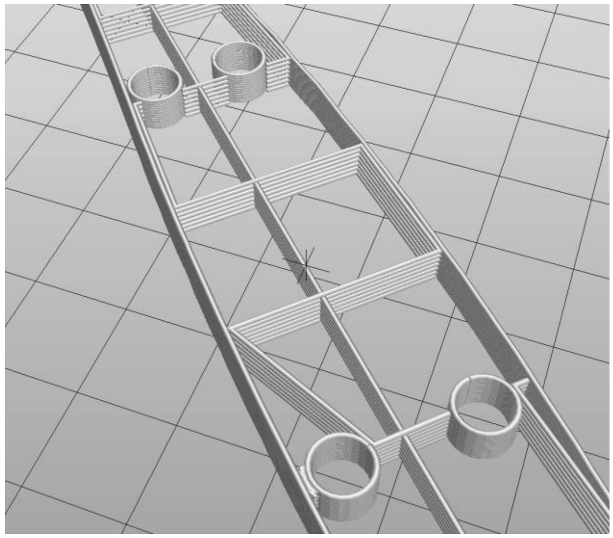

Figure 11: Winglet G_CODE detail from 70 to 82 Z layer.

The main checked features of the Winglet part are:

- 1 path perimeter is the minimum shape.
- Connectors have been reinforced by the infill.
- One side Infill extra perimeter has been drawn to ensure fixation.
- Central spar reduces spars high, therefore reduces buckling issues.

8.1.4 Winglet 3D printing

The first winglet printing process using the RepRap BCN 3D with white 3 mm PLA filament has been a 4 hours and 49 minutes process, less than previous estimated time. First layers have been manufactured with the connectors, see Figure 12, and 1 path perimeter have been success while fixation between layers has ensured a smooth airfoil shape. Important aspects of this stage have been:

- One tube connector has been designed to close to the perimeter path and material retraction has deformed the skin Surface. This problem will be solved in next stages.
- Trailing edge has printed a linear wrinkled razor indicating a minimum limit for this technology.

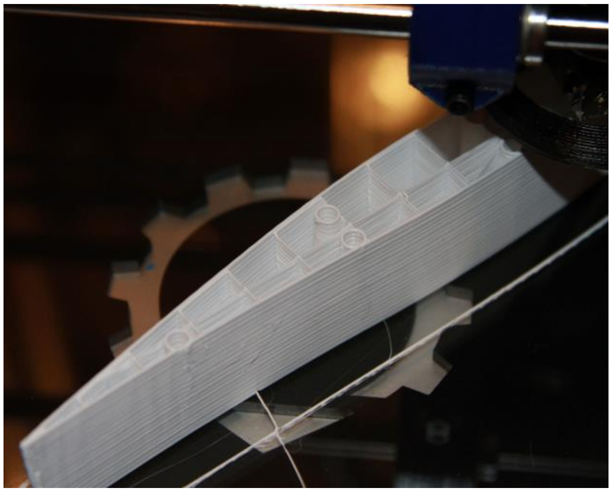

Figure 12: +0.25mm Z axis Winglet printing process.

Manufactured Winglet part is interesting because a cantilever shape has been 3D printed without support material, meaning a correct basement fixation. Z axis layers of 250 µm is the fastest printing process. See Figure 13.

The total time for printing is exactly the same as estimated adding 15 minutes, the time for heating extruder and bed. After printing, cooling duration is only 5 minutes to be able to remove the part.

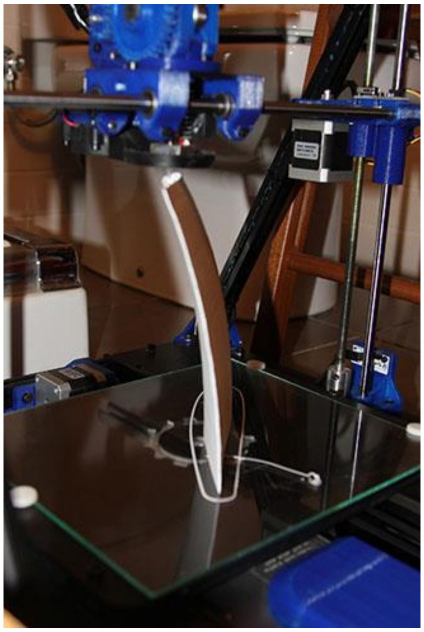

Figure 13: Winglet printing process.

This is an important step for this study because that is the first and most complex UAV part. When a new technology is used for the first time the uncertainty during the process of creating the first piece is high and felt an inevitable pressure. Since it has been made, when this point is exceeded, the next phase is to optimize and to improve the process.

8.2 AILERON WING PART

The aileron is a 185 mm Z printer axis length part. Manufacture this piece is simple compared with winglet, but CAD design is a complex transition taper adaptation in order to smooth wing skin. Aileron piece is the description name, but it has not an aileron system since this wing model is able to coordinate turns without it.

8.2.1 Aileron CAD design

Aileron part CAD design, see Figure 14, has been meshed by SWEEP command, extruding an airfoil polyline in a curved path with a splined taper. This method is as simple as LOFT and could be used in large nonlinear 3D solid pieces.

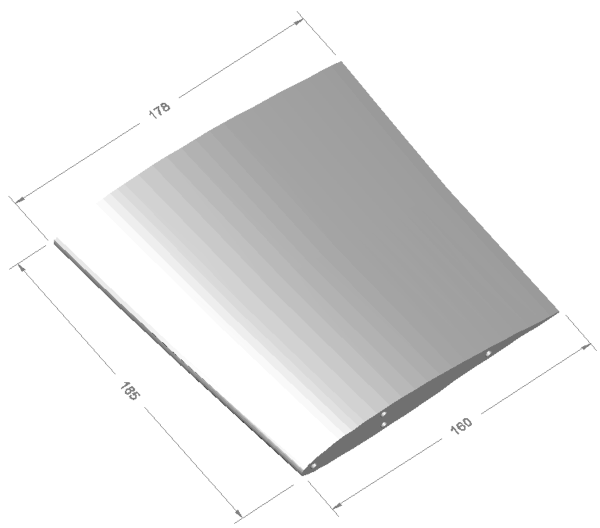

Figure 14: Aileron CAD Design [mm]

Connecting tubes between aileron and winglet have been reduced from 6 to 4 because of weight optimization while these are 25 mm clamp length. In the other side, we have maintained 6 original designed holes and 30 mm clamp length because of the highest stress requirement and the poor quality of the top face for nonsupport material printing process.

8.2.2 Aileron STL

Aileron STL is a 103 KB file with the information of a closed surface. The main properties have been listed in Table 10. Comparing with the winglet part, aileron is simpler, with less triangles number, but bigger in volume and surface.

Volume:	402.5999 cm³	Area:	721.5024 cm²
Points:	1142	Edges:	3420
Triangles:	2280	Shells:	1
Holes:	0	Bad edges:	0
Boundary edges:	0	Boundary Length:	0.00 mm
Flipped triangles:	0		
Surface is closed:			Yes
Surface is orientable:			Yes

	Min:	Max:	Ø:	Dev:
Edges/Point	3.00	18.00	5.99	1.33
Triangles/Edge	2.00	2.00	2.00	0.00
Triangle Quality	0.00	0.99	0.12	0.13
Edge Length	0.23	103.58	20.89	19.70

Table 10: Aileron part STL file information

8.2.3 Aileron G-CODE

The aileron G_CODE parameters (see Table 11) has been adjusted to a value filler reinforcements align with the connecting pipes and just a solid top coat because this part is in the middle.

Part	Winglet 1
Date	02/04/2014
Software	Slic3e 9.10b
Layer height	0,25
Perimeters	1
Top solid layers	1
Bottom solid layers	1
Fill density	0,0253
Perimeter speed	90
Infill speed	60
Travel speed	200
Nozzle diameter	0,4
Filament diameter	2,92
Extrusion multiplier	1,1

Perimeters extrusion width	0,53 mm
Infill extrusion width	0,53 mm
Solid infill extrusion width	0,5 mm
Top infill extrusion width	0,3 mm
First layer extrusion width	0,39 mm

Table 11: Aileron 1 G-CODE parameters

Aileron part is 1.54 times winglet volume and infill have been 66% reduced, therefore specific material volume is 0,125, a quarter of winglet specific material (see Table 12).

AILERON 1	
Printing time	4h 59m 59s
Filament used	7.512,9 mm
Material volume	50,3 cm^3
Part volume	403,46 cm^3
Specific material volume	0,125
Cost	2,52 €

Table 12: Aileron 1 G-CODE features

Connectors in the upper and lower sides have been supported by the filling through an iterative process as the software Slic3r does not allow the user to choose its position. Since tubes cannot be open during assembly process, one layer circular caps has been programed and added to G-CODE file, see Figure 16

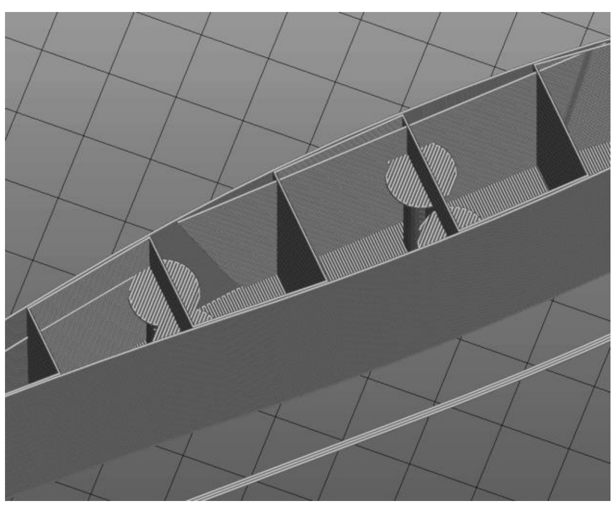

Figure 15: Designed connecting tube caps

8.2.4 Aileron 3D printing

This part is called aileron but it has not this mechanism, therefore it is a simple piece to be 3D printed. The main interest of this printing process is the tube caps result; see Figure 16. The circular shape is not an accurate circle as it has been printed without support material, but the result has been correctly solved with a lightweight layer.

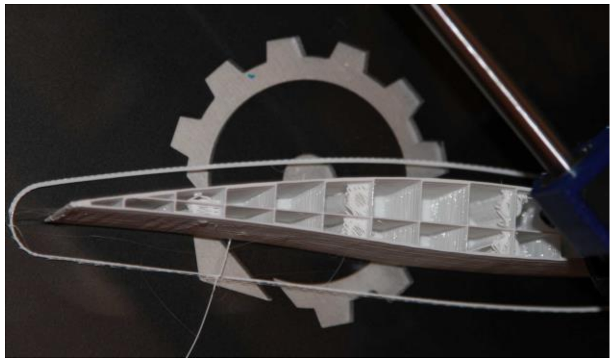

Figure 16: Printed caps for connectors

8.3 FLAP WING PART

Flap part is the third element of the wing, between root and aileron. The special feature of this element is the structural addition of a glass fiber tube because of the mechanical properties of the wing. Taper, twist and dihedral are lower than winglet part making it as simple as aileron shape in order to be designed and manufactured.

8.3.1 Flap CAD design

Flap has been designed in previous Autodesk software stage by 3D modeling commands. Since it is a middle part, there are connecting holes in both sides and the glass fiber reinforcement only in the root side. See Figure 17.

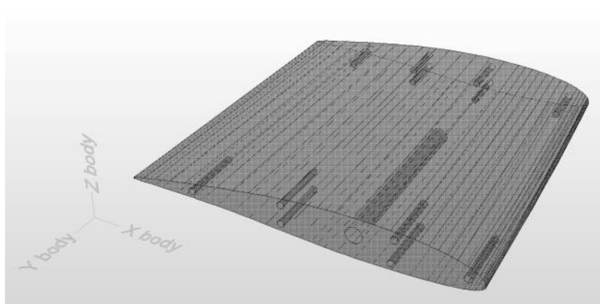

Figure 17: Flap part CAD

Plat part is 185mm Z printer axis length, 196 mm root-side section chord and 178 mm aileron-side section chord, therefore a total part and 0.9 taper ratio. Connectors are 4 mm diameter and 35 mm length holes ready to fix wing parts.

8.3.2 Flap STL

Flap STL is 98 Kb file with the shape information. Triangles and points define the boundary layer between inside and outside, including holes of lateral sides. From Table 13 information Flap area versus volume ratio is 1.71 cm^{-1}. This is an important value of the lightweight wing performance fixed by the airfoil. Therefore, G_CODE algorithm is the only way to improve part weight. This study must be focused on this performance after first wing will be a real thing able to be evaluated in its precision and weight.

Volume:	492.5058 cm³	Area:	842.5547 cm²
Points:	998	Edges:	2988
Triangles:	1992	Shells:	1
Holes:	0	Bad edges:	0
Boundary edges:	0	Boundary Length:	0.00 mm
Flipped triangles:	0		
Surface is closed:			Yes
Surface is orientable:			Yes

	Min:	Max:	Ø:	Dev:
Edges/Point	3.00	16.00	5.99	1.50
Triangles/Edge	2.00	2.00	2.00	0.00
Triangle Quality	0.00	0.99	0.14	0.17
Edge Length	0.29	139.79	24.76	29.38

Table 13: Flap part STL file information

8.3.3 Flap G_CODE

The Flap G_CODE parameters (see Table 14) has mainly adjusted the infill value to 0.022. Iteration infill process allows the wing part and glass fiber reinforcement stresses transmission.

Part	Flap 1
Date	04/04/2014
Software	Slic3e 9.10b
Layer height	0,25

Perimeters	1
Top solid layers	1
Bottom solid layers	1
Fill density	0,022
Perimeter speed	90
Infill speed	60
Travel speed	200
Nozzle diameter	0,4
Filament diameter	2,92
Extrusion multiplier	1,1
Perimeters extrusion width	0,53 mm
Infill extrusion width	0,53 mm
Solid infill extrusion width	0,5 mm
Top infill extrusion width	0,3 mm
First layer extrusion width	0,39 mm

Table 14: Flap 1 G-CODE parameters

Flap is 234.351 lines code file that contains total CNC information; see Table 15. After 3 parts have been programmed by CNC generator code, it is possible to discover a key feature of 3D printing technology compared to traditional processes: the direct time, cost and weight relationship. The report document has paid attention to this amazing, but obvious, performance.

FLAP 1	
Printing time	5h 10m 19s
Filament used	8954,3mm
Material volume	60,0 cm^3
Part volume	492,5 cm^3
Specific material volume	0,122
Cost	3,00 €

Table 15: Flap 1 G-CODE features

G-Code simulation shows the Flap specific infill against the glass fiber reinforcement in two-printer axis X-Y. Distance between walls is a constrain value defined by infill percent, therefore once we have centered cross Z line in the GF tube, it is not possible to reinforce all connecting-parts tubes. In Flap case maximum airfoil thickness ones.

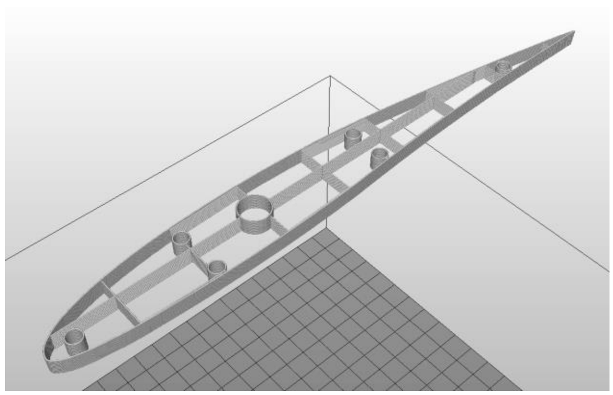

Figure 18: Flap G-CODE simulation

8.3.4 Flap 3D printing

Flap 3D printing phase has taken near estimated time and infill performance. Figure 19 shows GF reinforcement aligned with infill walls. It is not exactly centered, but it is correct because the figure is in the 122,25 mm Z layer manufacturing moment and dihedral path is not aligned with the infill.

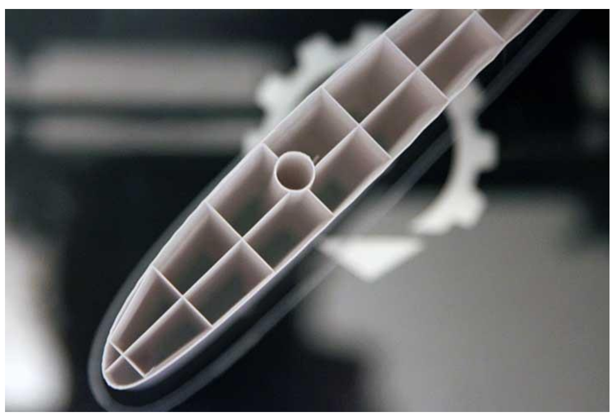

Figure 19: Flap 3D printing process

8.4 ROOT WING PART

First root wing test will try to be flight tested in a high-density foam fuselage, the original Multiplex Easy Star II. It means designed airfoil transition to digitalized fuselage hole have to be solved by CAD.

8.4.1 Root CAD design

Root part CAD design, see Figure 20, has been meshed by LOFT command parameters, between two cross sections, to create the transition surface. This part of 200 mm chord and 185 mm length finish to the symmetry plane. Fuselage insertion has been bitten to allow wires transfer and Y axis movement prevent.

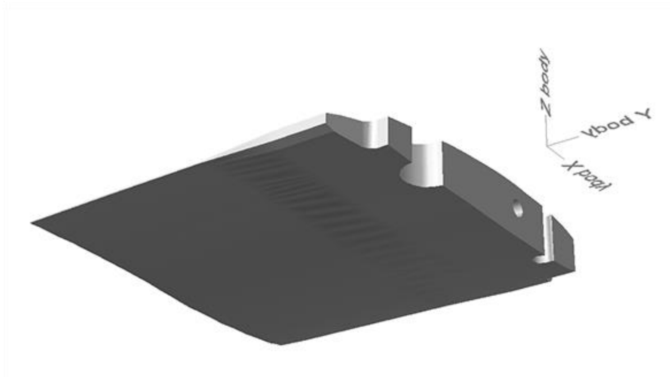

Figure 20: Root CAD Design

8.4.2 Root STL

Root STL, see Table 16, is the maximum volume part of the wing, but it is only 55% of winglet triangles number. This performance has been achieved by optimizing the designed CAD parametritzation by polygons vertices alignment in one of the two-airfoil axis, in this case the body axis Z.

Volume:	603.2566 cm³	Area:	900.1286 cm²
Points:	1019	Edges:	3057
Triangles:	2038	Shells:	1
Holes:	0	Bad edges:	0
Boundary edges:	0	Boundary Length:	0.00 mm
Flipped triangles:	0		
Surface is closed:			Yes
Surface is orientable:			Yes

	Min:	Max:	Ø:	Dev:
Edges/Point	3.00	16.00	6.00	1.89
Triangles/Edge	2.00	2.00	2.00	0.00
Triangle Quality	0.00	1.00	0.20	0.23
Edge Length	0.12	185.00	23.34	28.94

Table 16: Root part STL file information

8.4.3 Root G-CODE

The aileron G_CODE parameters (see Table 11) has been adjusted to a value filler reinforcements align with the connecting pipes and just a solid top coat because this part is in the middle.

Part	Root 1
Date	07/04/2014
Software	Slic3e 9.10b
Layer height	0,25
Perimeters	1
Top solid layers	1
Bottom solid layers	1
Fill density	0,025
Perimeter speed	90
Infill speed	60
Travel speed	200
Nozzle diameter	0,4
Filament diameter	2,92
Extrusion multiplier	1,1
Perimeters extrusion width	0,53 mm
Infill extrusion width	0,53 mm
Solid infill extrusion width	0,5 mm
Top infill extrusion width	0,3 mm
First layer extrusion width	0,39 mm

Table 17: Root 1 G-CODE parameters

Root part is the most expensive part, see Table 18, with 3.31 € cost, including filament and energy cost, but lowest specific material ratio. It is an important feature for next stages development because total weight and cost will be compared with Multiplex model to study the feasibility of 3D printing technology.

ROOT 1	
Printing time	5h 8m 37s
Filament used	9.871,9 mm
Material volume	66,1 cm^3
Part volume	603,26 cm^3
Specific material volume	0,11
Cost	3,31 €

Table 18: Root 1 G-CODE features

Special difficulties of this part are top layers because they work in a cantilever material deposition. This study has developed two algorithms to manufacture this complex bridges without support material and author have called them: Tree and Cheddar. Explained in the 3D printer Annex.

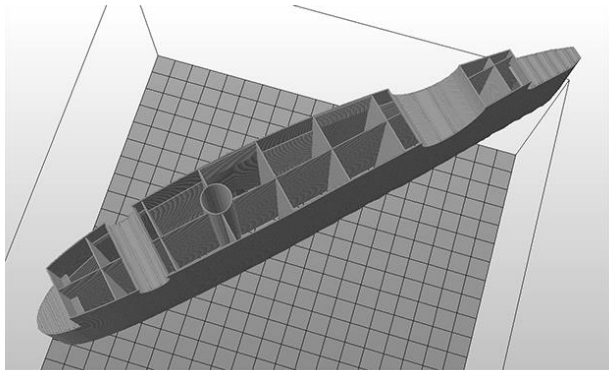

Figure 21: Root 1 G-CODE simulation

8.4.4 Root 3D printing

The 3D printed part, see Figure 22, has the perfect shape to be embedded in the wing allowing engine wires duct cross. Upper layer is degraded cause of using a single layer, this is not in contact with the air stream and its function is to prevent deformation of the profile in X-Z body axis when it is inserted into the fuselage.

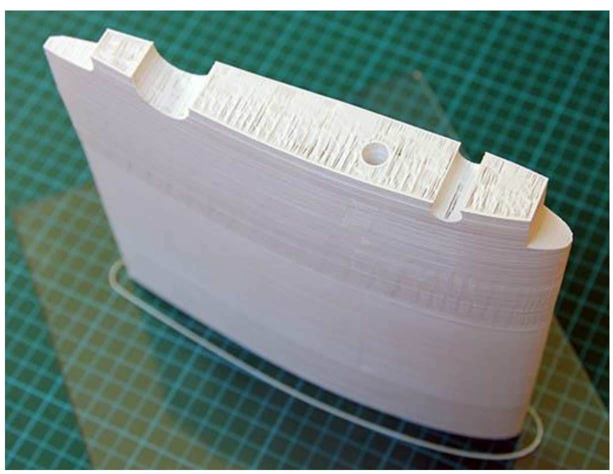

Figure 22: Root 1 3D printed result

8.5 PARTIAL SUMMARY

Four half-wing parts have been rightly manufactured with the selected technology; see Table 19. Reprap BCN 3D+ printed have worked continuously without important problems but start printing bed calibration. This process has shown:

- Complex shapes have been supported.
- Support material has not been used.
- Perimeter accuracy is half extruded diameter, ± 200 μ.
- High speed printing requires 250 μ Z layer steps.

Half wing 1	
Material	White PLA
Printing time	20h 21m 38s
Filament used	32.641,4 mm
Material volume	218,6 cm^3
Weight	273,3 g
Cost	10,93 €

Table 19: First half wing specifications

8.6 ASSEMBLY PROCESS

Since we have the four half wing parts, see Figure 23, it starts the assembly process. It is an important stage of the study because of the small 3D printing size that makes it necessary to create big parts.

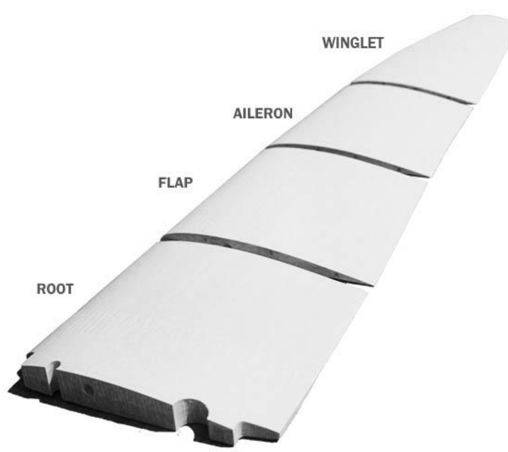

Figure 23: Half wing four parts

Provided connectors have been 4 mm dimensioned and, obviously, aligned between parts. Union requirements have been:

- Support structural requirement, at least wing properties.
- Lightweight.
- Flexible, in order to be absorbed wing vibrations.

According to requirements, connectors used have been 3 mm Carbon fiber tubes because of the mechanical properties versus weight ratio and silicon adhesive because of the elasticity required to ensure a flexible union, see Table 20.

WING ASSEMBLY 1		
Connectors	Material	CFRP
	Diameter	3 mm
Adhesive	Material	Silicone
	Elasticity (DIN 53504)	250%
	Tensile strength	20 Kg/cm2

Table 20 Wing assembly specifications

Assembly process has started from tip parts to the root. CFRP tubs have been cut by standard steel saw, in a difficult process because of the inexperience of the author of this study, have been painted with adhesive silicone and inserted into provided holes.

Figure 24: Winglet with added CFRP connectors

After 8 hours of curing, tensile test has broken provided hole, not the union. This test has demonstrated that designed union has high tensile performance than 3D printed parts, like desired.

Figure 25: First half wing weight measurement

Final half wing is 291 g weight; see Figure 25, 3.88 times high density foam Multiplex Easy Star II wing. Taking into account 1500 mm 3D printed wingspan versus 1385 mm compared model wingspan, it would be less, but any way wing design must be weight optimized. The first test has been useful to improve knowledge about 3D printing technology and be able to better adjust printer configuration, design, G-CODE generation and unions.

9 2nd WING MANUFACTURING TEST

The aim of the second manufacturing test is to reduce weight while supporting structural requirements. Previous test has been modified in the right direction in order to optimize the infill, internal reinforcements. Second half wing modifications have been resumed in Table 21.

Description	VOLUME	FILAMENT	DURATION	RATIO	Cost
Units	cm3	mm	h:m:s		€
WINGLET	31,2	4.666,3	4:57:57	0,119	1,56
AILERON	48,6	7.255	4:59:57	0,120	2,43
FLAP	57,9	8.647,4	5:13:45	0,118	2,90
ROOT	63	9.141,7	5:06:24	0,104	3,15
TOTAL (avg.)	**200,7**	**29.710,4**	**20:18:03**	**0,115**	**10,04**

Table 21: Summary table of second half wing test

Iteration process has been used to adjust minimum infill to ensure airfoil shape. Winglet filament used have been reduced to 74% and other parts only 95%, the reason is low aerodynamic loads of the winglet, tip of the wing, allowing an only 1 internal wall instead of first test 9 walls. An important structural modification has been the 45 degrees infill; see Figure 26. The reason is the use of the two direction wall to support X body axis aerodynamic lift torque, first test had unused walls aligned to airfoil chord.

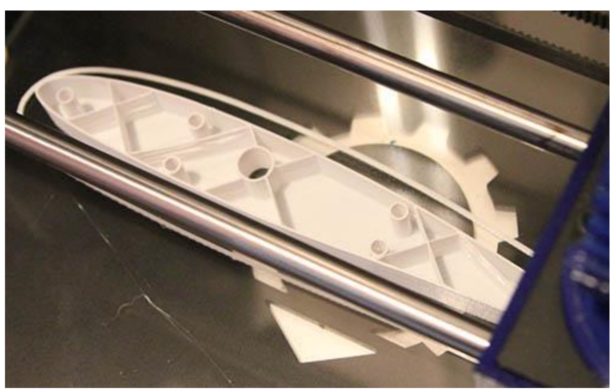

Figure 26: 45 degrees second test infill

The assembly process has been modified by 3 mm Nylon connectors instead of CFRP. The reason is the cost reduction and the enough mechanical properties of the connectors since 3D printed parts do not require composites tensile strength.

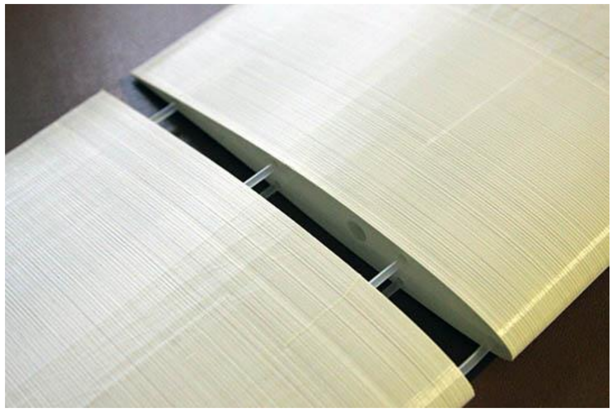

Figure 27: Nylon second wing test connectors

Second weight test has been measured at 265 g (see Figure 28) 91% of the first test. It is an important reduction, but it is still too high, 3.5 times the Multiplex foam model. Since infill is optimized and CAD design is an unalterable shape, this study must develop another joining system to reduce weight and adhesive curing time.

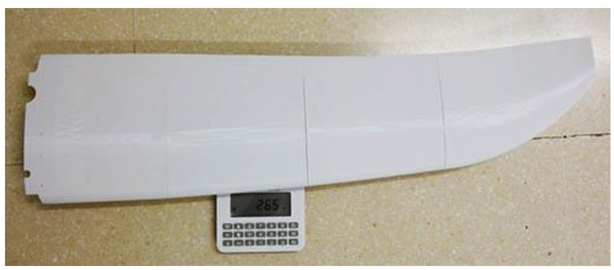

Figure 28: Second half wing weight measurement

10 3rd WING MANUFACTURING TEST

The aim of the third manufacturing test is to develop a welding system for PLA parts. Methodology must reduce weight while supporting union requirements and reduce time because small printing size requires parts union to become UAV models.

10.1 Welding PLA methodology

This study has focused the effort in trying different welding PLA techniques. The requirements to select the methodology have been:

- Rapid.
- Low cost.
- Easy.
- Ability to undo.

The alternatives considered have been: adhesives, hot air, ultrasounds and heat. After any alternative tests:

- Cyanoacrylate super glues do not work on PLA.
- Epoxies are a hassle, take a long time to set, and not as strong as the rest of printed part.
- Hot air tools melt too much material, make good joints very difficult to achieve, and cannot fill gaps.
- Ultrasound have not been tested because UAV manufactures big parts and this technology needs to fix them in a small space.
- Heat with a soldering iron using this rod as filler material ensures high mechanical properties and long lasting joint weld pieces together.

A take decision method has not been needed since the only technique that supports welding requirements is the heat with soldering iron. This study has used a Ratio (7604 R1) tin welder with 30 W power, 230 V and 50 Hz. See Figure 29.

Figure 29: RATIO 7604 R1

Welded parts have been tested with a dynamometer in order to know the tensile strength of the union and, only welding from one side; load supporter is higher than Z axis printed surface. The reason is that melted PLA is distributed in all directions when welding instead of one direction-printing filament.

Used welding method allows manual filler material and the 3D printer starts with a one-layer ring of lost material. Leftover PLA have been the input. See Figure 30. Warning: contact with high iron temperature is dangerous for human skin and near objects.

Figure 30: PLA welding test with filler material

PLA welding technique has been carefully used in the third wing test eliminating connection tubes, adhesive, PLA provided holes, PLA ribs and curing time.

10.2 3rd WING TEST SUMMARY

Compared with second test, new version is 73% previous weight. Demonstrating that it has been worth the effort to develop a lightweight welding system. At the same time, printing has been 1 hour reduced. See Table 22.

Description	VOLUME	FILAMENT	DURATION	RATIO	Cost
Units	cm3	mm	h:m:s		€
WINGLET	26,5	3.956,6	4:43:14	0,101	1,33
AILERON	36,4	7.255	4:59:57	0,090	1,82
FLAP	43,1	6.436,7	4:44:26	0,088	2,16
ROOT	44,9	6.705,7	4:45:29	0,074	2,25
TOTAL (avg.)	**150,9**	**24.354**	**19:13:06**	**0,088**	**7,55**

Table 22: Summary table of third half wing test

Third half wing has been 194 g weight; see Figure 31, an amazing reduction by changing parts union technology. This version is 2.58 times the basic foam wing and now it is interesting to consider the different wingspan in order to accurate weight ratio.

Since third root part is 185 mm large, 67.4 g weight and 3D printed wingspan is 115 larger, we can reduce root part in 57.5 mm meaning 20.95g weight reduction. Computed 173 g half wing weight is only 2.31 times the high-density foam model.

Figure 31: Third half wing weight measurement

Feasibility of 3D printing in UAV applications depends on the weight. Therefor this study must go further in weight reduction and the only way left is 3D printer configuration and Arduino programming.

11 4th WING MANUFACTURING TEST

The aim of the forth wing version is to adjust CNC configuration in order to reduce wall thickness in the Z printer axis. Modifications have been adjusted for the extruder engine since it deposits an optimized thinnest filament while layer path movement. Welding technology has been previous test one.

11.1 UAV Specific CNC program

New 3D printer Reprap BCN 3D+ configuration file have been initially G-CODE programmed with next configuration:

 # generated by Slic3r 1.0.0RC2 on Thu Apr 8 16:01:38 2014 by Jonatandomenecharboleda

avoid_crossing_perimeters = 0

bed_size = 230

bed_temperature = 53

bottom_solid_layers = 2

bridge_acceleration = 2000

bridge_fan_speed = 100

bridge_flow_ratio = 1

bridge_speed = 80

brim_width = 0

complete_objects = 0

cooling = 1

default_acceleration = 1500

disable_fan_first_layers = 2

duplicate = 1

duplicate_distance = 6

duplicate_grid = 1,1

end_gcode = M104 S0 ; turn off Hot End\nM120 S0; turn off Hot Bed\nM140 S0\nG1 X230 Y210 E0; \nM84 ; disable motors *external_perimeter_speed = 60*

external_perimeters_first =

extra_perimeters = 1

extruder_clearance_height = 20

extruder_clearance_radius = 20

extruder_offset = 0x0

extrusion_axis = E

extrusion_multiplier = 1

extrusion_width = 0

fan_always_on = 1

fan_below_layer_time = 30

filament_diameter = 2.92

fill_angle = 0

fill_density = 0.05

fill_pattern = rectilinear

first_layer_acceleration = 1000

first_layer_bed_temperature = 55

first_layer_extrusion_width = 130%

first_layer_height = 0.3

first_layer_speed = 40

first_layer_temperature = 220

g0 = 0

gap_fill_speed = 20

gcode_arcs = 0

gcode_comments = 0

gcode_flavor = reprap

infill_acceleration = 2000

infill_every_layers = 1

infill_extruder = 1

infill_extrusion_width = 0

infill_first = 0

infill_only_where_needed =

infill_speed = 60

layer_gcode =

11.2 4th WING TEST SUMMARY

This test shows how 3D printing technology has led to optimal end for UAV applications. Since this moment weight could only be reduced in a low percentage requiring a huge effort and time, therefore author has considered it is enough to evaluate feasibility of this technology, aim of this study.

Last half wing test have been 154 g weight, 2.05 times specific high-density foam. Double ratio-values between 3D printed PLA and high performance foam have been developed in a wing shape, a high surface versus volume part. See Table 23.

Description	VOLUME	FILAMENT	DURATION	SD RATIO	Cost
Units	cm3	mm	h:m:s		€
WINGLET	21,2	3.166,5	4:42:22	0,782	1,06
AILERON	30,4	4.546,3	4:35:29	0,871	1,52
FLAP	32,6	4.869,4	4:44:11	0,789	1,63
ROOT	39,15	5.844,6	5:43:57	0,894	1,96
TOTAL (avg.)	**123,35**	**22.562**	**19:45:59**	**0,839**	**6,17**

Table 23: Summary table of 4th half wing test

12 ULTIMATE LOAD WING TEST

The Ultimate Load test of the 3D printed wing has been made in the Mechanical Properties Department LAB of the ETSEIAT University. Testing tools, method and help, see Figure 32, has been facilitated by Dr. Lluís Gil Espert, professor of this Department.

Figure 32: ETSEIAT Structures department laboratory

The ultimate load wing test, see Figure 33, is a static test in which the wing is deflected to simulate the Ultimate Load, beyond or at which the wing is expected to fail [6]. This test result will be a UL empiric value. Since this test is for a UAV, a safety factor is not required.

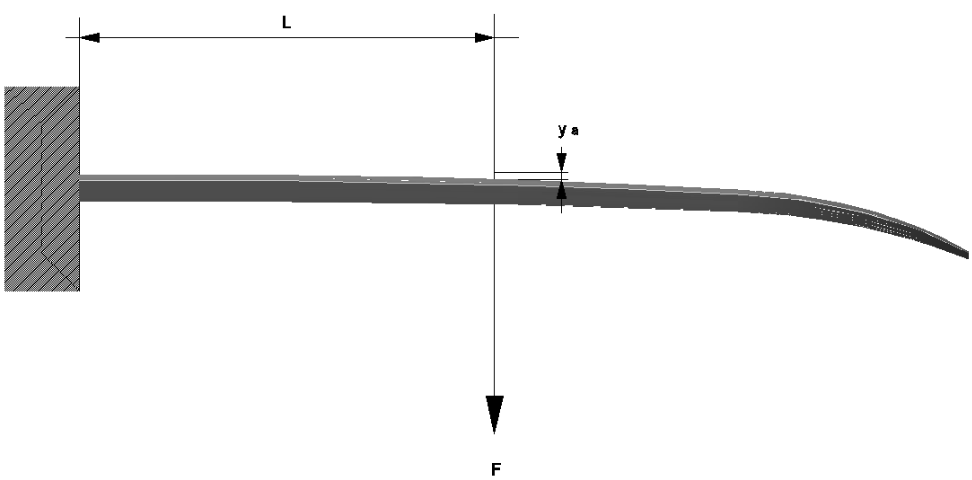

Figure 33: Cantilever 3D printed wing scheme

The wing has been fixed, from Y=125mm, and a Force has been applied to 300mm distance from the support. While adding mass, any deformation of the wing has been measured with ±0.5 mm precision tool. The first load has been the support weight, 359.24 g, and next steps by 100 g increments, see Figure 34, becoming a destruction test in the 9th case.

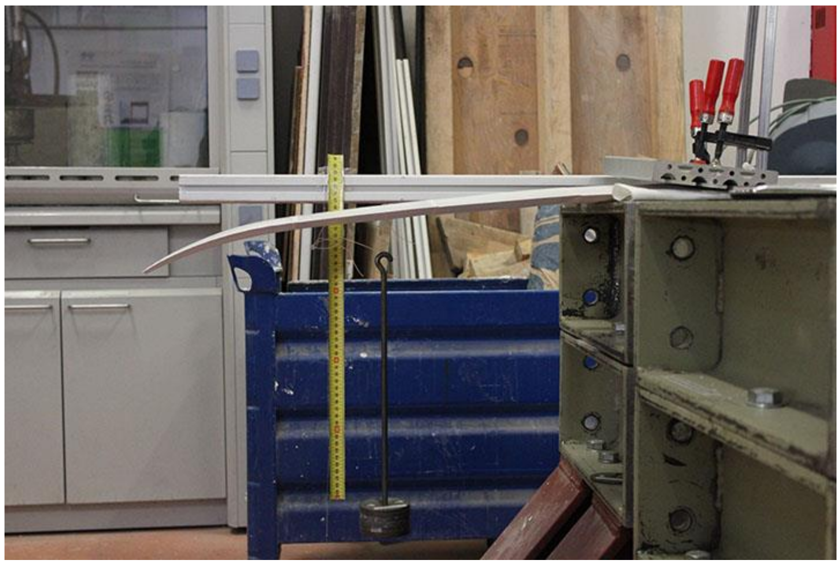

Figure 34: Wing testing process photo

Test data has been enumerated in Table 24. It shows that the maximum load has been 11.4 N, equivalent to 1.16Kg mass. This maximum load has been supported by the wing for more than 3 seconds before collapse.

Factor	Unit	1st	2nd	3rd	4th	5th	6th	7th	8th	9th
Weight	g	359.24	459.24	559.24	659.24	759.24	859.24	959.24	1059.24	1159.24
Force	N	3.5	4.5	5.5	6.5	7.4	8.4	9.4	10.4	11.4
Deformation	mm	12	13	15	17	19	21	23	26	28

Table 24: Experimental DATA values

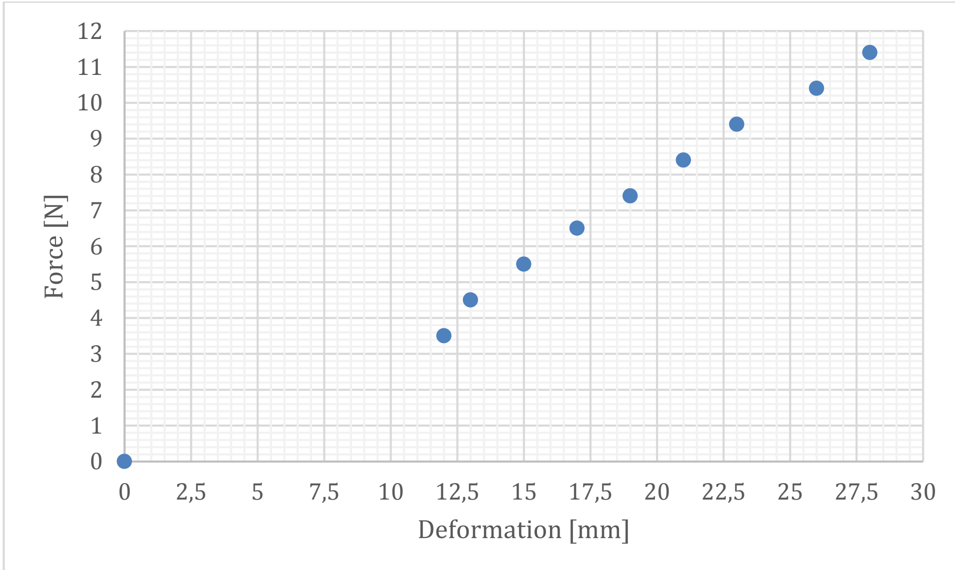

Table 25: Experimental DATA graph

In order to be able to check and validate experimentation data it is required an analytic development of the Ultimate Load test. The wing has been estimated as a cantilever beam with defined axis orientation. EN is the neural axis, α is angle EN-Z. See Figure 35. Navier-Bernoulli hypothesis has been considered: slice edges maintained parallel and perpendicular to the directive vector.

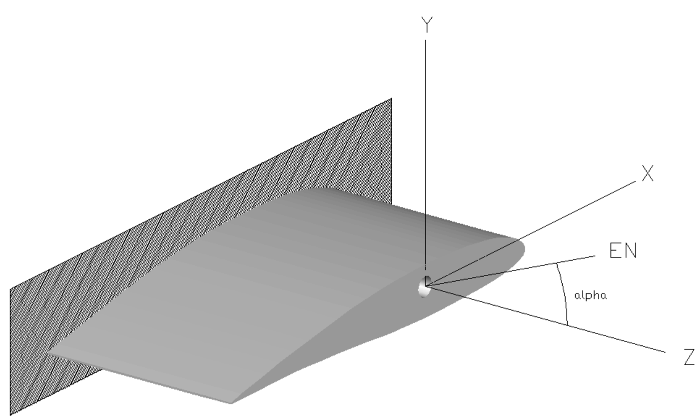

Figure 35: Ultimate Load test axis

For this section, normal stress σ_z will be different in any point (x, y) of the slice according to next equation:

$$\sigma_z = \frac{M_x}{I_x} \cdot y - \frac{M_y}{I_y} \cdot x \qquad (II)$$

Where area momentum I_x and I_Y and area product I_{xy} have been defined as:

$$I_x = \int_A y^2 \, dA \qquad I_y = \int_A x^2 \, dA \qquad I_{xy} = \int_A xy \, dA \qquad (III)$$

In the inertial principal axis area product will be zero, others have been defined in the simple expression by equivalent momentum $\dot{M}_X$ and $\dot{M}_Y$, becoming next equation and taking into account that axial load, Z axis, is not required in wing operation:

$$\sigma_z = \frac{\bar{M}_x}{I_x} \cdot y - \frac{\bar{M}_y}{I_y} \cdot x \qquad (IV)$$

According to previous equations and knowing that the wing has been broken from root slice, from the equilibrium balance, at the support there is a resisting moment –FL and a vertical upward force F. At any point along the beam the moment is:

$$F(z - L) = Mx = EI \, \frac{d^2 y}{d^2 z} \qquad (V)$$

Integrating twice and zeroing constant term, because in the first integration dy/dz=0 at z=0 and in the second integration y=0 at z=0:

$$ya = -\frac{F}{EI}\left(\frac{L^3}{2} - \frac{L^3}{6}\right) = -\frac{FL^3}{3EI} \qquad (VI)$$

Where E is the Young’s modulus = σ/e (N/mm^2), *y* is the distance of surface from neutral one (mm), I is the moment of inertia (mm^4) and F is the force (N). This equation has the hypothesis of constant section, thereby the wing must be discretized, see Figure 36.

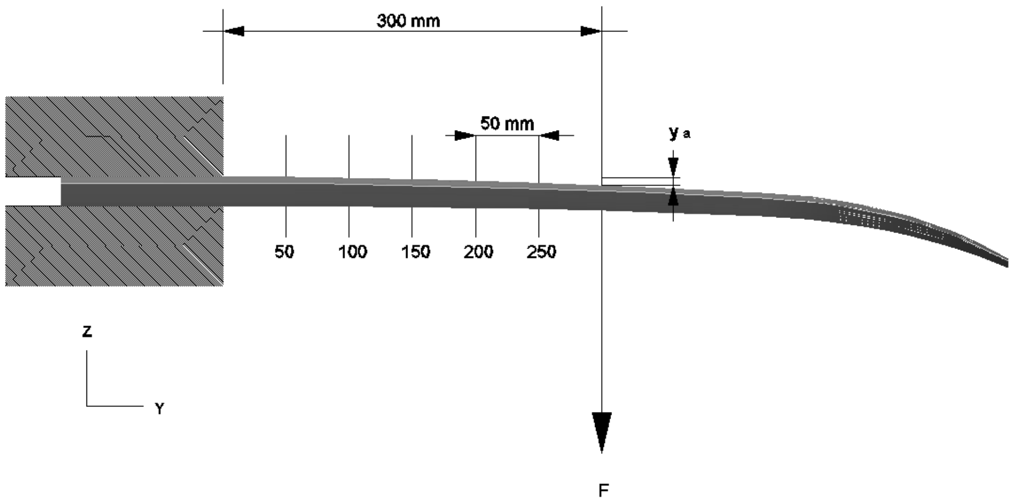

Figure 36: Analytic test discretization

Young Modulus[11] has been tested in a previous stage, see attachment: ANNEX IV, where it has been demonstrated that PLA, when printed, is an anisotropic material, with different behavior in the MD or TD layer orientation. In the airfoil plane the orientation has been the X-Y printing axis slice, thereby the layering orientation is transversal. According to this, E (TD) =420MPA.

Figure 37: Infill wall detail

[11] *YOUNG MODULUS is a measure of the stiffness of an elastic isotropic material.*

Infill, see Figure 37, has been programmed by specific G-Code parameters. It has been configured to be printed in even number layers. Therefore 50% wall performance cannot be estimated for the moment of inertia, because once the Infill wall has been deformed, threads adhesion is broken and in the next load solicitation mechanical properties changes.

Moment of inertia in the support has been computed from the data file. The area has been evaluated using perimeter thickness, estimated in previous testing stage: 600 µm, and differential of length: distance between data points. The infill and reinforcement cylinder supports, see Figure 38, have been computed separately.

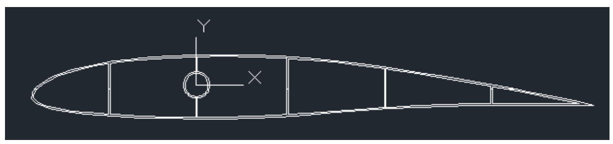

Figure 38: Support wing section

According to previous hypothesis, the X inertial moment of the wing in the support of this test has been computed in 17840 mm^4. The same process has been used in any section of the wing differentials.

- *Area:* *297.7485*
- *Perimeter:* *1000.6151*
- *Bounding box:* *X: -58.4858 -- 140.7080*
  Y: -11.9352 -- 10.6568
- *Centroid:* *X: 34.6174*
  Y: -1.7836
- *Moments of inertia:* ***X: 17840.2868***
  Y: 1252119.4611
- *Product of inertia:* *XY: -33426.4509*
- *Radii of gyration:* *X: 7.7406*
  Y: 64.8482
- *Principal moments and X-Y directions about centroid:*
  I: 16635.5740 along [0.9999 -0.0171]
  J: 895565.8955 along [0.0171 0.9999]

Since the wing section is not constant along the wing, the test evaluation has estimated 6 differentials of wing with the hypothesis of constant section, showed in Figure 36. The deformation has been evaluated in each differential for each force of the test.

Y (mm)	0	50	100	150	200	250	300
Iy (mm4)	17840	16419	14997	13576	12155	10733	9312

Table 26: Discretized Inertia

The deformation in the 6 differential volumes has been computed for every Force case with the justified Young modulus, E (TD) =420MPa, and each moment of inertia, see Table 27.

dy	Iy	0	3.5N	4.5N	5.5N	6.5N	7.4N	8.4N	9.4N	10.4N	11.4N
0	17840	0.00	4.20	5.41	6.61	7.81	8.89	10.09	11.29	12.49	13.69
50	16419	0.00	2.64	3.40	4.15	4.91	5.59	6.34	7.10	7.85	8.61
100	14997	0.00	1.48	1.91	2.33	2.75	3.13	3.56	3.98	4.40	4.83
150	13576	0.00	0.69	0.89	1.09	1.28	1.46	1.66	1.85	2.05	2.25
200	12155	0.00	0.23	0.29	0.36	0.42	0.48	0.55	0.61	0.68	0.74
250	10733	0.00	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11
Total deformation [mm]		**0.00**	**9.28**	**11.93**	**14.58**	**17.24**	**19.62**	**22.27**	**24.93**	**27.58**	**30.23**

Table 27: Analytic DATA deformations

Experimental and analytic data have been compared; see Table 28, showing the validation of the test. Experimental data slope is according to 550MPa Young modulus and it is possible since PLA tensile test TD sample was 3D printed with 0.8mm thickness and wall measurements have evaluated 0.6 mm thickness. Experimental data do not cross origin because of 2 reasons:

- Wing is made by different parts welded, union section could change be damaged after first load case.
- Infill has been designed by printing 50% of layers thereby, when charged, it could be a micro break phase.

However the aim of this test has been to carry out a wing test in order to know if an extra reinforcement is required. Ultimate load of the half wing test has shown that the wing has been broken, after more than 3 seconds, when 1159 g weight. Therefore total wing in static operation, not flying, supports 2318 g. This load performance has been related to the supported G factor by estimated UAV weight.

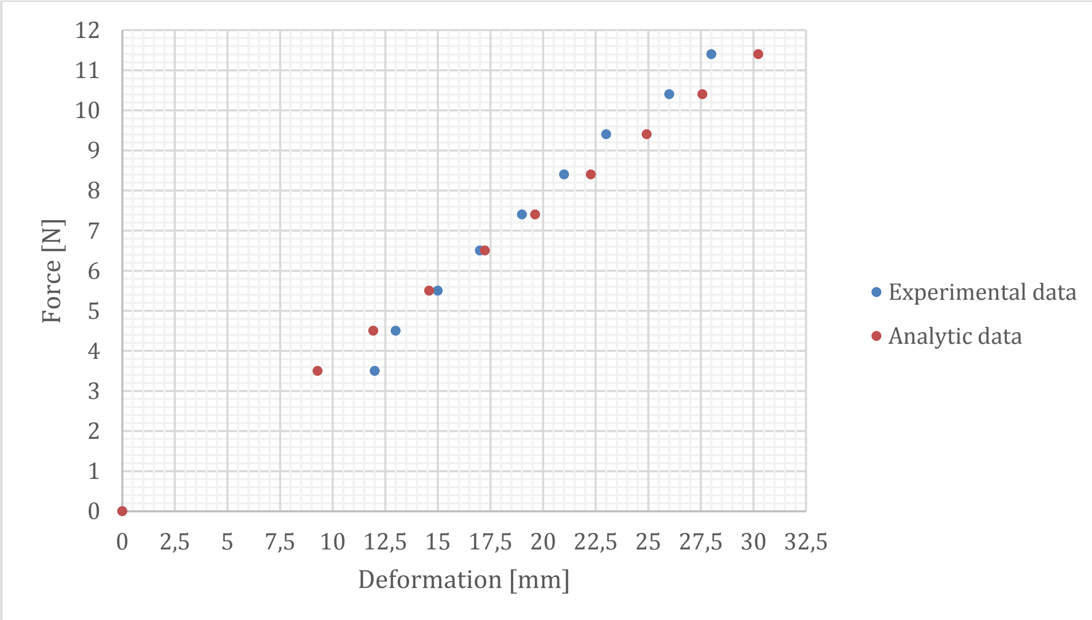

Table 28: Data comparative graph

G factor estimation, with 1440 g operational weight, has been +1.60G. This is a poor value that could only supports cruise operation, but turbulence, climbing or looping. Since project aim is to flight a 100% 3D printed UAV, the wing must be reinforced to avoid wing collapse, see Figure 39.

Wing joiner has been designed by GRP, Glass Reinforced Polymer, tubular of 8 mm diameter, 1 mm thickness and 579 mm length; the same as Easy Star II aeromodel.

Figure 39: Destructive Ultimate Load test

This static test has become an important stage for the 3D printed wing. Since it has demonstrated that reinforcement is required, the perimeter thickness of the wing surface could be reduced, becoming a better weight performance of this technology.

13 WING FLIGHT TEST

April, 11th 2014 have been a key date of this study because 3D printer manufactured wing was tested in a real flight with a MULTIPLEX high density foam fuselage, see Figure 40.

Figure 40: 3D printed wing flight test

The available wing were half wing of any version, thereby the flight test used a 2nd version for the left half wing and the 3rd version for the right one. This unbalanced wing was solved by adding extra mass in the light version. According to this, the wing weight for the flight test was 530 g, higher than the 308 g weight of the last version wing.

Jordi Santacana, CATUAV director, was the pilot and his expert comments were:

- 3D printed wing has had an excellent aerodynamic performance.
- Wing weight must be reduced.
- It is an important step in the 3D printing technology for UAV applications.

First suggestion has been important because it means that the used infill maintain the airfoil shape in flight operation. An extra weight is not required to avoid wing deformation.

Second suggestion has been solved since the last version is 58% of the tested one, the best weight performance has not been tested in this stage..

Third comment is pure energy for this study to go on with 3D printed technology for UAV applications and has encourage the author to try to develop a 100% 3D printed UAV.

14 CONCLUSIONS

This Annex document shows that the weight performance of the 3D printing technology is feasible for UAV applications.

The evaluated factors of weight versus volume parts demonstrates that this study is able to improve the worldwide lightest existing 100% model, VAST UAV from MIT University and Air Force of USA.

The material used, PLA, is an excellent material for this wing application although it is 123% ABS density. The reason is that PLA is biodegradable and the duration of the decomposition has been referenced by 180 days, it means that heavy tested wing versions are compostable, according to the environmental friendly aim of this study.

Designing a fuselage with the standard shape, near cylinder, will become a heavy UAV not able to compete with high-density foams technology like ELAPRON®, therefore some development in fuselage design will be required.

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June 2th, 2014

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