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Application of Additive Manufacturing to the production of RPAV components

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Abstract

The current work is based on the activity of “Team S55”, an engineering student team of the Politecnico di Torino, that has the aim of building a remotely piloted (RPAV) 1:8 scaled model of the Savoia Marchetti S55X, an iconic seaplane made famous by a series of record-breaking long-distance flights.
Advanced materials and innovative technologies have been used to comply with the weight requirement of the FAI-F4C competition, imposed at 15 kg empty weight without batteries.
The purpose of this work is to show the advantages of the application of Fused Deposition Modelling (FDM) and Selective Laser Melting (SLM) during the construction process.
The FDM process is applied to the production of molds for the composite (carbon fiber) parts.
To reduce the weight and cost of the mold, topological optimization was used to calibrate the typical process parameters such as infill density and internal fill path considering the constraints imposed by the polymerization process with vacuum bag.
The SLM process of aluminium alloy AlSi10Mg has been selected to manufacture the engine support of the seaplane.

Keywords: UAV, Additive Manufacturing, Mold, Engine Mount

1. Introduction

“Team S55” was born in 2017 in partnership with “Replica55” project and its main aim is to reproduce the historic S55 seaplane. The S55X seaplane is a catamaran configuration, equipped with twin engines, one pulling, one pushing. Three rudders surmounted a tailplane linked to the fuselage by four beams. There were several versions available of the S55 for civil and military use, but this one (distinguished by the X) was made to celebrate the tenth anniversary of the foundation of the “Arma Aeronautica”. In the 1933 the “Decennale” air cruise was organized: under Air Minister General Balbo’s leadership, twenty-four S-55X (and an auxiliary one) flew from Orbetello, Italy to Chicago, across the Atlantic Ocean, to attend the "Century of Progress" Exposition. The fleet “covered 6100 miles in a flying time of 47 hours and 52 minutes”, with only one accident occurred. Representative John P. McSwain, Chairman of the House Military Affairs Committee said about this feat: "No 'round-the-world trip of any war-ship or fleet has ever impressed the people of the whole world as this spectacular flight of 24 planes.

At the beginning the student team “Team S55” was composed by only a few students, whose task was focused on the analyses, by means of FEM, of CAD drawings (Figure 1) produced by “Replica55”, which were related to the original engineer Alessandro Marchetti’s project **[1].**

After the initial phase, the interest in this program increased and was going beyond the just numerical analyses and the team of the Politecnico di Torino grew in terms of participants and objectives. In fact the team, in parallel with the structural, aerodynamic, hydrodynamic and flight mechanics investigations, decided to design and manufacture a 1: 8 scale replica of the S55X seaplane. The aircraft model, whose wingspan is 3 m span, refers to original Cad drawings, including new construction techniques and modern materials (Figure 1). One of the team's objectives is to participate, with its own aircraft, in international competitions for model aircraft, such as the F4 Scale World Championship **[2].** These competitions have very specific requirements both as regards the aesthetics of the model aircraft (the similarity with the original aircraft is an evaluation criterion during the race) and as regards their maximum weight and the technical characteristics of the systems. The current rules impose a MTOW (Maximum Take-Off Weight) of 25kg that oriented the design toward the use of very light materials, but at the same time resistant and functional to the possibility to operate with specific flight capability in performing specific maneuvers according to the competition criteria and requirements. In consideration of all this, composite materials (in particular carbon fiber, and sandwich of glass fiber and foam) were chosen for almost all parts of the aircraft; while wood and canvas were used for the tail and ailerons to recreate the aesthetics of the original.

Figure 1: S55X Original CAD

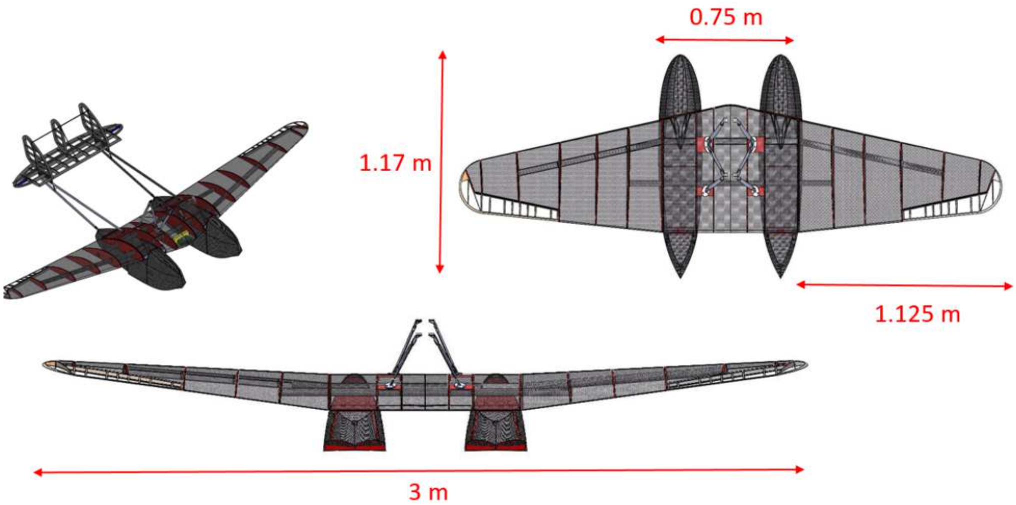

Figure 2: 1:8 S55X Scaled Replica

Additive manufacturing technology is introduced for the manufacturing of moulds necessary for the lamination process and to manufacture the engine mount structure in a single piece. The idea starts from the consideration that virtually there are no additional costs associated with an increase in complexity with the advantage to tailor the design specifically to the relevant case or application.

2. Innovative moulds solutions

The extensive use of composite materials necessary to build the 1:8 scaled model has also required a specific investigation on the manufacturing process in order to built the specific lamination moulds. The traditional mould production technique is based on the mechanical milling of metallic or plastic materials. It required a lot of time, high production costs and limitations in the design (the limits of the machines must be taken into consideration). On the contrary, the production of moulds through AM (Additive Manufacturing) technology allows a considerably costs reduction, a decrease in manufacturing time (the CAD file model can be used as input to the 3D printer and then to the final item), but above all, the design choices are largely improved (although there are still technological limits to be taken into account), and moreover the complexity of design does not affect production costs. Additional requirements as references for alignment of others items, multi-component moulds to solve problems of "negative angle" in integrated structures, ventilation ducts, housings for mechanical inserts and so on, can be easily included in the mould design phase without relevant and significant cost increasing. Furthermore, the possibility of manufacturing the mould, directly at the production site, allows a considerable reduction in costs and times in case of redesign **[3].**

Despite the different types of additive manufacturing processes available, the fused deposition modelling (FDM) is one of the most used and dates back to the 80s **[4,5].**

For the choice of the mould material, numerous factors have been taken into account: above all, the large amount of material that would be needed to produce a large number of moulds and also of considerable dimensions, the ease of printing of the material and obviously the cost of the material that must be included in the project budget. For these reasons, the PLA (polylactic acid), was chosen, being a low-cost, biodegradable and simplest material to be printed. ABS has been evaluated, as an alternative, but rejected for its tendency to generate the phenomenon of warping during the printing process and also for safety issues related to the emission of toxic fumes during printing. Pet-g, was rejected for its mechanical properties lower than PLA. PLA imposes technological limits on the use of moulds, this is because it has a low glass transition temperature (60 ° C) and a high CTE (thermal expansion coefficient, 436 μm / m ° C), therefore it is not possible to use an autoclave for the polymerization process. For our purposes, however, the quality of the composites obtained by room temperature curing cycle, with vacuum bag enclosing the complete mould plus laminate, are considered adequate for the prototype manufacturing. A material that can be used for autoclave curing process is ULTEM 1010 (glass transition temperature of 215°), but its price (about 300 euro/kg) is not cost-effective for the proposed use **[6].**

Another aspect to be taken into consideration for the production of the moulds is the size of the printing chamber, which limits the maximum size of the workable piece and consequently it may be necessary to create joints for assembling different parts and completing the entire mould. These joints are of particular importance because they affect the surface finishing. In our experience it was quite difficult to keep all of them under control, a complication added by the fact that the current PLA cannot be easily reworked by abrasion. Moreover PLA with inclusion of reinforcement materials suitable for post-working activity is available on the market showing improved mechanical characteristics and is re-workability by means of commercial sanding paper, but the cost is out of the available budget then usual PLA. In the proposed configuration the final configuration has been finished by adding materials by means of a 3D pen. The first manufactured moulds were those of the half-wings (figure 1). Each half-wing was divided into 2 parts (upper and lower skin), each of which still consists of 6 pieces; this was necessary due to the considerable size of the half-wing (850*550 mm) with respect to the printer chamber (300x400x300 mm). The various pieces were then assembled by means of joints (PLA "butterfly" shaped joints and wooden dowels),the assembled items were reinforced by threaded bars (figure 1). Once the assembly was completed, a 3D pen was used to fill some gaps between items. Since the pieces are of considerable size, the printing times were also quite long, so a 1 mm diameter nozzle was chosen instead of the standard 0.4 mm nozzle. This option required changes to the printing process parameters. the extrusion temperature of the PLA filament was increased to 220 ° C, temperature of 60 ° C of the printing bed was chosen and the extrusion speed was decreased to 30 mm/s. Indications on the times and costs for the production of the wing mould are included in table 1.

Due to significant changes in the usual printing parameters, the surface roughness of the moulds was verified; the results obtained were in line with the expectations. The roughness in the direction of item growing (90 °), was greater compared to the horizontal direction (0 °). The figure 4 shows an example of a roughness profile obtained from the measurements. The values obtained are in agreement with what is reported in **[7]**, better roughness can be obtained by a post-process surface finishing in order to meet typical tools requirements.
Finally the lamination of half-wing was performed at room temperature by means of epoxy resin and using a vacuum bag. The lamination is made by 3 layers of 200g carbon fabric (+-45) and one of glass fiber 40g for the external part of the covering. In figure 5 is reported the final result for the whole wing covering configuration.

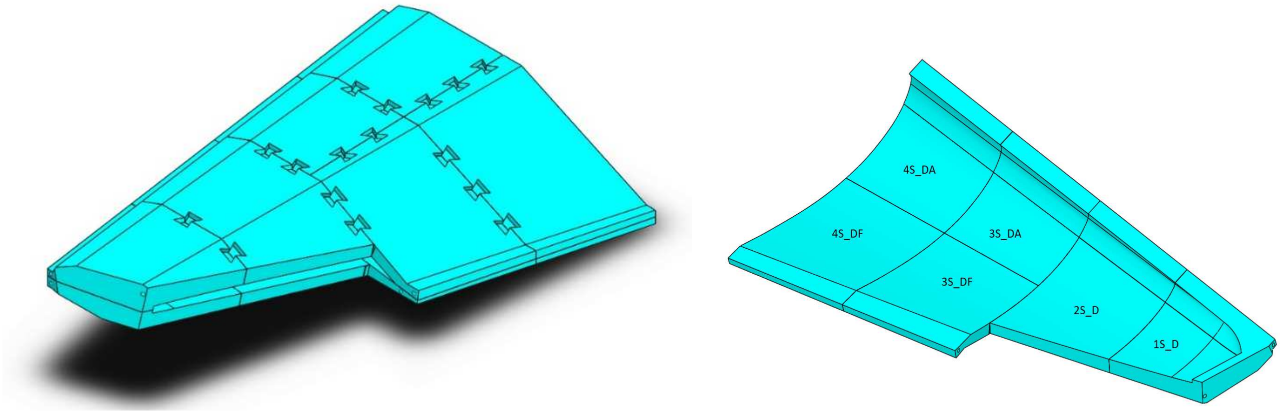

Figure 2 Wing mould concept & left wing upper surface sections

Section	Printing time [h]	Weight [g]	Cost [euro]
1S_D	18	644	12,24
2S_D	25	946	17,98
3S_DA	18	640	12,16
3S_DF	22	789	15,00
4S_DA	18	635	12,06
4S_DF	24	829	15,75

Table 1: wing mould sections time, mass and costs

Figure 3: upper wing mould assembled and ready for roughness measurements.

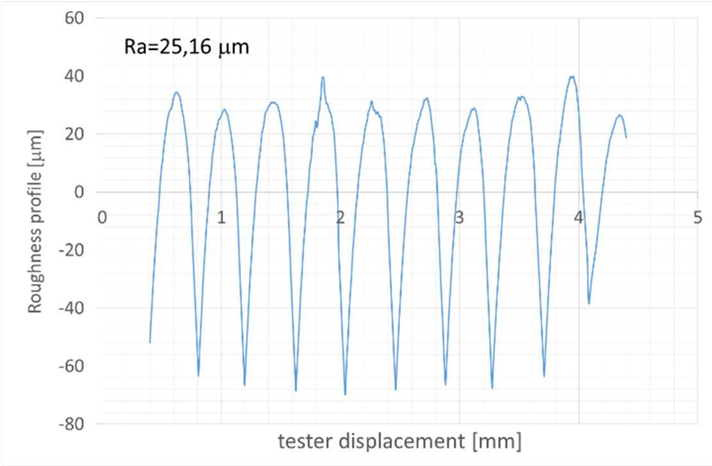

Figure 4: Roughness measurements by RTP80

Figure 5: upper wing skin - hand layup and vacuum bag

A male mould was prepared for the hull lamination. This choice was due to two main factors: a) significant reduction in time and production cost, b) no significant differences in the surface of the laminated items finishing between the mould-contact surface or not mould-contact. Due to the highly curved hull surface some changes were performed to the mould assembly techniques. External bolts were used for mould items assembly and cyano-acrylic adhesive applied. The gaps between mould items were filled using the 3D pen, but HIPS (High Impact PolyStyrene) was used instead of the PLA. The use of HIPS improves the surface reworking by sandpaper. HIPS is also soluble in Limonene so this property permits a lamination on male HIPS mould and its subsequent removal by Limonene. A combined process of soluble HIPS and Nylon reinforced with Carbon can be considered a very promising configuration if the final item requires a combination of high and low strength areas. This combined approach was evaluated for the design optimization of the horizontal stabilizer ribs also in the case of Topological optimization procedure. An overall view of the model is presented in figure 6 and moulds printing time and costs are reported in table 2.

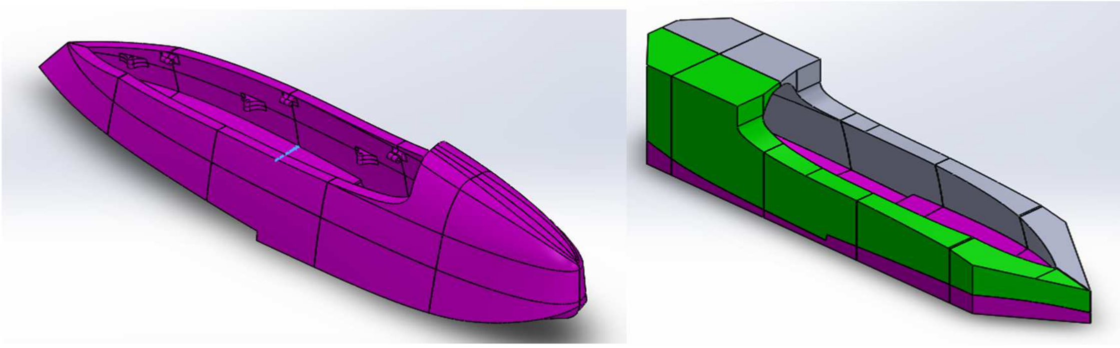

Figure 6: male & female moulds concepts

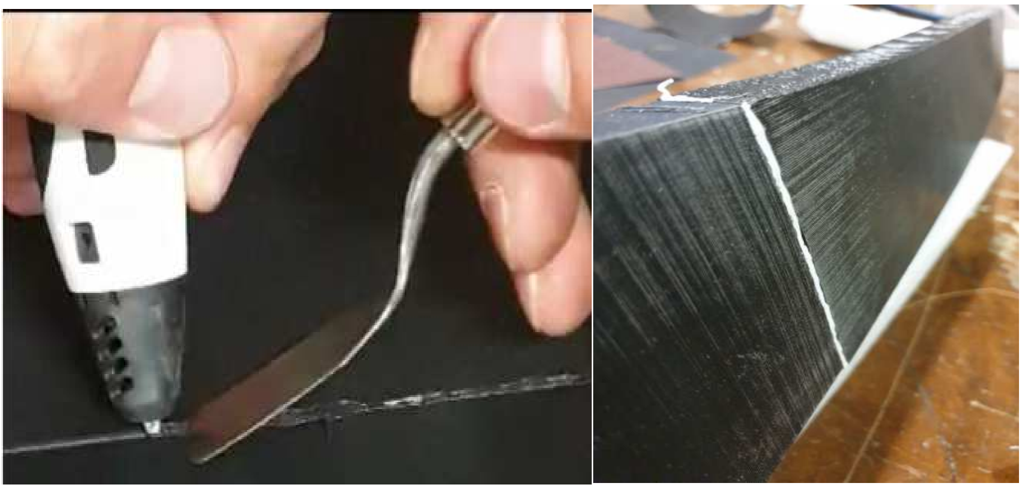

Figure 6: 3D pen soldering operations and particular of hull mould soldered with HIPS

	Female	Male
Estimated time (h)	208.69	120.7
Cost (€/Kg)	19	19
Estimated cost (€)	140.13	72.31

Table 2: Hull moulds printing time and costs

3. Process parameters setup

In the FDM process, a circular nozzle, that move in x and y planes by multi-speed is numerical controlled to generate each two-dimensional (2D) layer and extrude these from a spool thermoplastic filament material or composites with thermoplastic materials to semi-molten state processes. The filament materials are fed into the liquefier through a set of two mechanical freewheels driven in a counter rotating mode, which delivers enough torque to the thermoplastic filament material to perform as a piston during the extrusion stage and then deposit it layer-by-layer or path-by-path based on the 3D CAD model onto an adjustable build platform. The build platform holding the 3D printed sample and moves vertically downwards in the z plane to commence depositing a new layer/path on top of the previous one. The STL (standard tessellation language) file is exported directly in Solidworks with the maximum quality available, 2.6 ° for the angle tolerance (angle between the normals of adjacent triangles) setting and 0.02 mm for the deviation tolerance setting (the maximum deviation between the designed part and the STL representation of the part). After STL file is created the slicing software will produce a the G-code file readable from the printer.

In order to create a mould that minimizes the use of material and therefore of the cost but at the same time is able to maintain the desired roughness and geometric tolerances, the choice of slicer settings are very important and above all the selection of the geometry of the infill are of fundamental importance **[8].** In order to identify thickness and size of the internal mould repetitive cell structure and to select the correct parameters for setting the slicer, a topological optimization was carried out using the software Inspire from Altair **[9]**. The optimization was carried out on a two-dimensional finite element model and a first test was carried out on a 200X20mm flat mould specimen, loaded on the top with a uniform distributed load to simulate the vacuum achieved through the vacuum bag (approximately 1 atm) and fixed to the bottom. The goal of the optimization was to obtain a geometry that maximizes stiffness to limit as much as possible the geometry variations of the mould with a fixed infill level (volume occupied by the material with respect to the total volume). As an example in Figure 7 the case of an infill level fixed at 15% is shown. The reference material used in this preliminary analysis is a typical FDM technology printing material with modulus of elasticity of about 2000MPa and poisson's ratio equal to 0.35 and yield stress of about 45MPa. The model consists of a non-design zone on the outer perimeter of the mould with a thickness of 1mm (grey zone) and an internal design space (brown zone)

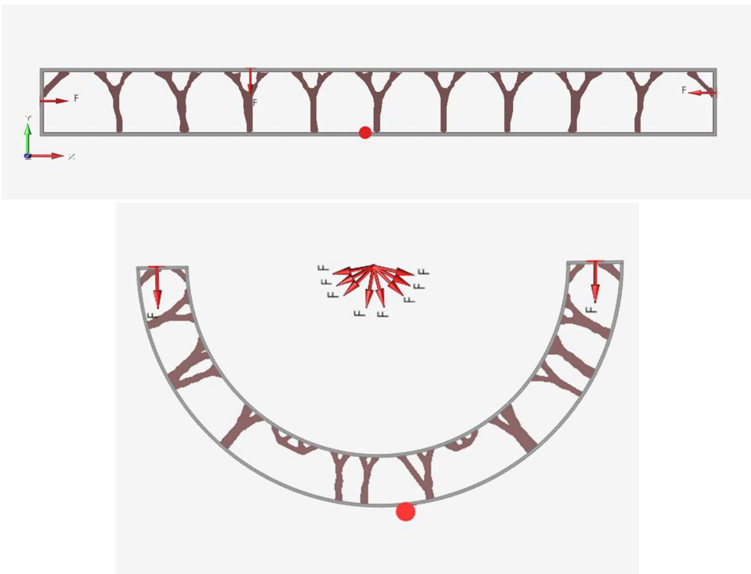

Figure 7 Optimized flat and curved sample with infill level at 15%.

The figure 7 shows that a columnar structure 1.2mm thick with a branch in the vicinity of the non-design space area seems to be the ideal solution. In this case the mould deflections are kept below

0,7mm and a minimum safety factor of 14 is obtained which means that the danger to have yield due to stress is avoided. A similar conclusion is obtained by considering a second test case representing a mould with a curved surface.
An additional consideration about structural instability must be made. A subsequent FEM analysis was made in order to verify the stability of the structures derived from the optimizer. The conclusion is that a reduction of the free length of deflection is necessary in order to avoid collapse due to instability. The final setting of the slicer therefore involves the insertion of columnar structures interrupted by horizontal stiffeners as shown in figure 8. The optimized parameters used for the wing mould are finally shown in table 3.

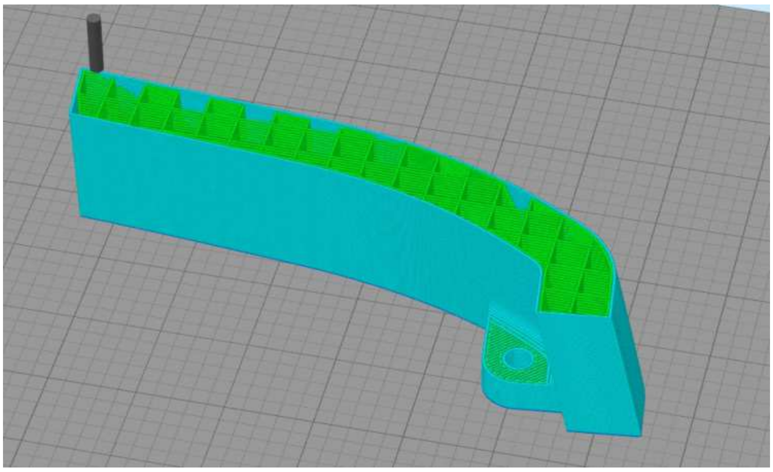

Figure 8: An example of slicing with the infill chosen.

Layer Height	0.4mm
Nozzle Temperature	220 °C
Bed Temperature	45 °C
Speed	30 mm/s
Infill	13 %
Perimeter	1

Table 3: Process Parameters

	Time [h]	Material [g]
Our Proposal	29,00	760
Solid Shell	34,5	893
Sparse Shell	41	1227

Table 4: Comparison between various approach

The solution adopted is also compared with two other techniques for making the moulds proposed in **[10],** the “sparse solution” and the “solid shell” solution. The proposed solution is compared on a semicircular specimen and results are shown in figure 9 and table 4.

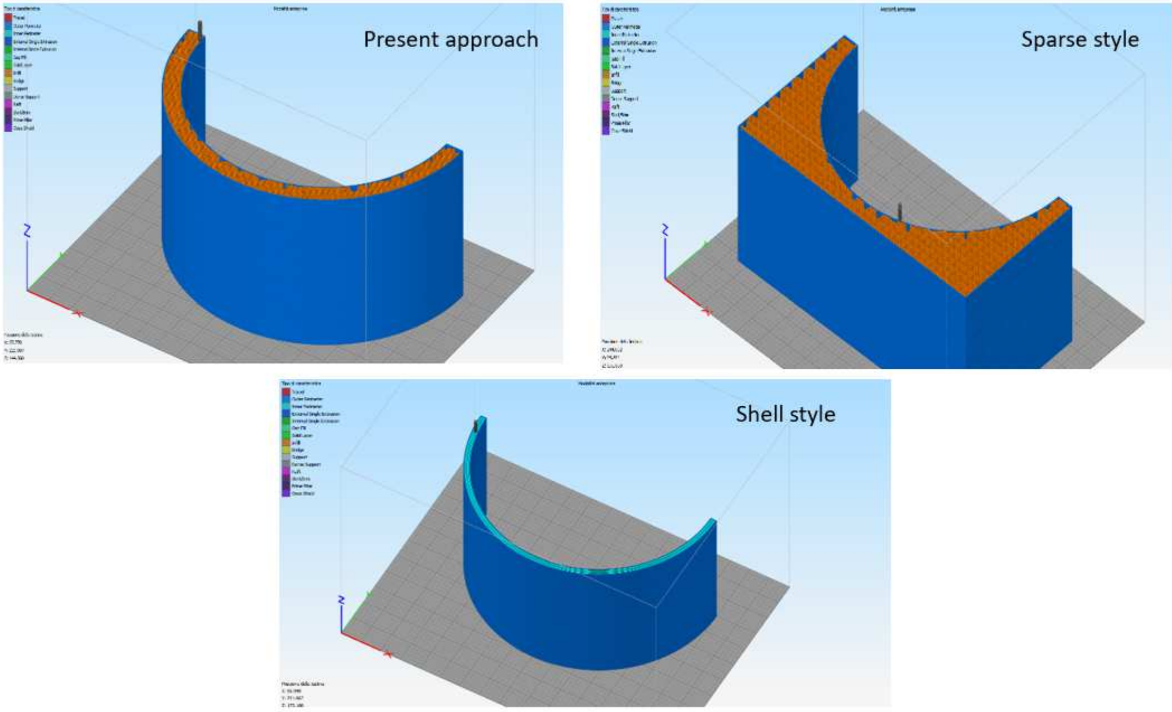

Figure 9: Present approach vs Sparse & Shell style

4. Engine Mount manufacturing

The engine mount structure was manufactured in a single stage in AlSi10Mg by selective laser melting. AlSi10Mg is an Aluminum alloy with good casting properties, young modulus of about 75GPa, yield stress of about 270MPa and density of 2670 kg/m^3, used for cast parts with thin walls and complex geometry **[11].**

Design started from the original CAD drawing of the piece, the 1:1 assembly is made of many parts including metallic parts, wood parts, bolts, and screws so it is quite complex and very difficult to reproduce in a 1:8 scaled prototype. The engine mount design was divided in three stages. The first design phase was the simplification of the original geometry to obtain a printable part. We start from the original CAD removing all the features that were non reproducible in a 1:8 scale. The original model of the Engine Mount has been optimized for weight saving considering that the current material used for the lower legs (AlSi10Mg) is mechanically more performant than the original wood and steel legs, the new design remains identical to the original design in the visible areas. The upper bridge original design was modified to provide a structural and functional optimization and to facilitate the two electrical engines installation.

Another part subjected to main modification were the base plates which connect the mount to the wing, they results too small when scaled so they must be enlarged a little bit to use a M3 bolt to attach the two parts to the wing skin. The truss engine upper area was also redesigned for weight saving. Main modifications are shown in figure 9. Engine mount structural element, 490 mm long and with a max height of about 300 mm, is considered complex from the manufacturing point of view, furthermore the cavity of the structural elements will be used for wires and cables routing. This design solution makes it particularly suitable for being made with SLM technology just in four pieces as shown in figure 10 where the slicing configuration and the real component during production are reported. Producing it with traditional techniques would require more assembly time with a considerably heavier final item.

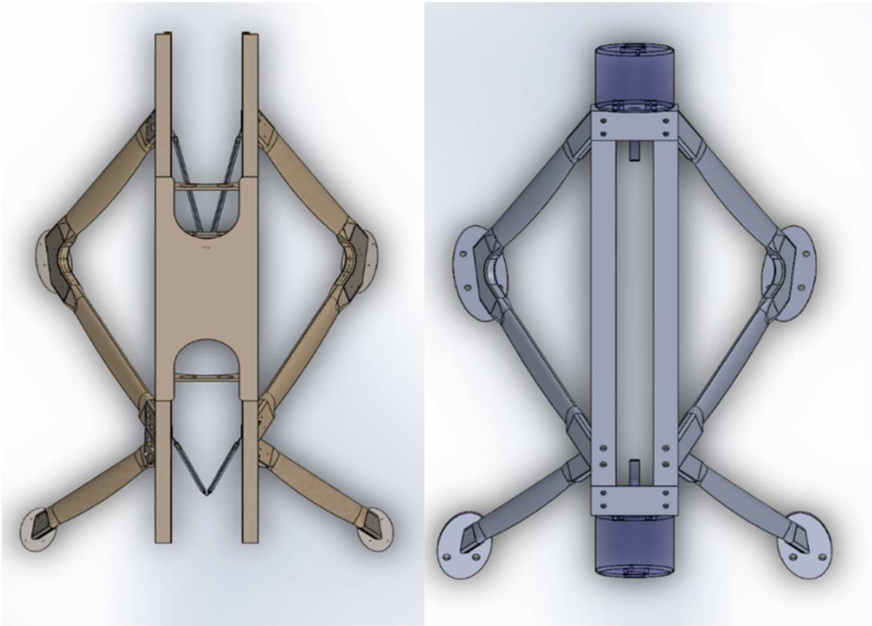

Figure 9: Engine mount design: left: original geometry right: simplified 1:8 geometry

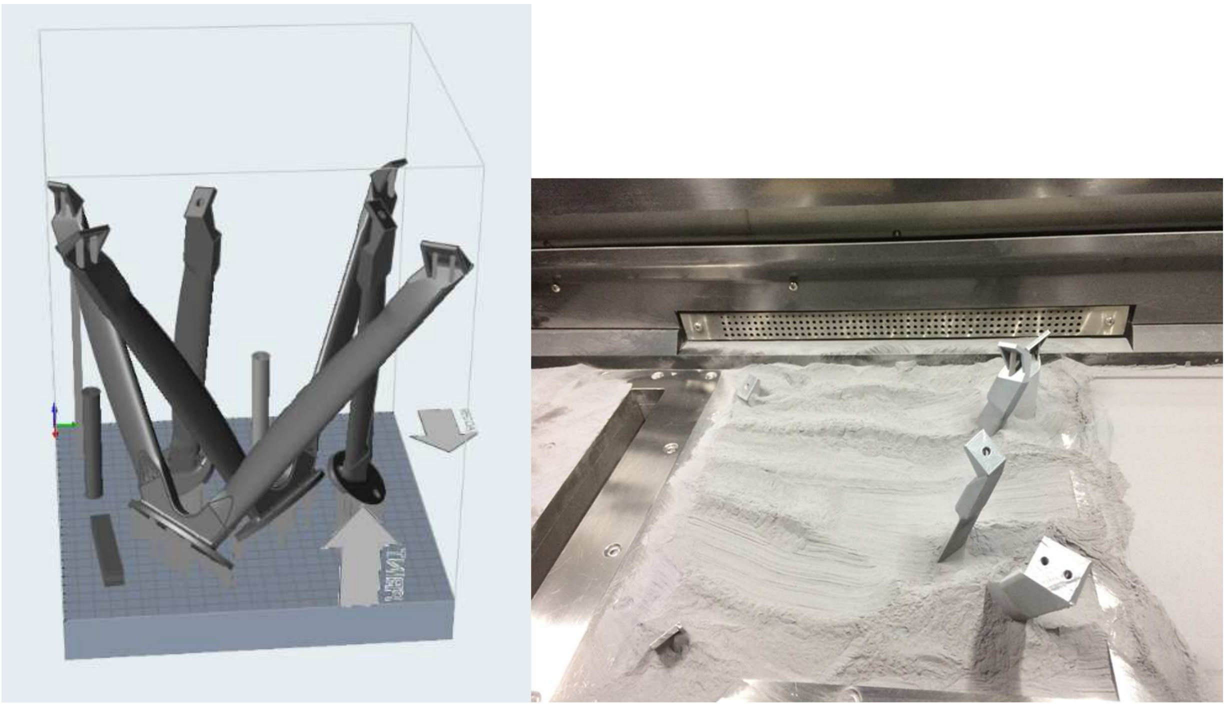

Figure 10: Printing setup and and pieces under production

Before production, the second fundamental design phase was the static and dynamic verification of the designed structure through finite element simulation. The performed static analysis confirmed the structural adequacy in the most critical conditions when subjected to the loads due to the thrust of the two counter-rotating propellers and the inertial loads during the ditching phase. Finally, in order to prevent dynamic coupling potentially dangerous for the stability of the system a modal analysis was performed. Figure 11 shows some FEM results of the static analysis. The results are very satisfactory with an average stress of 20 MPa and peaks of 30 MPa in the nominal case and a 50 MPa and 70 MPa in the ultimate case. The structure however cannot be made with less material because the minimum thickness of 1.2 mm is close to the technological limit of the SLM, fixed by the manufacturer to the limit of 1 mm. The displacements are also very low and compatible with the engine truss stiffness requirements.

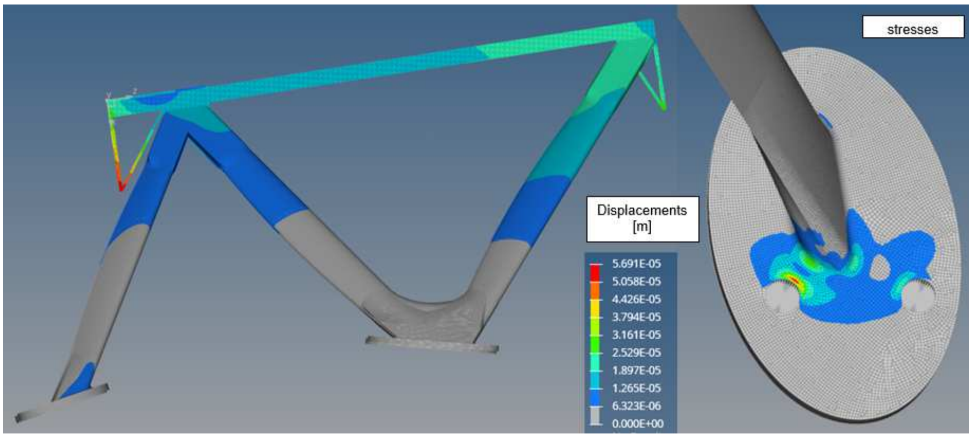

Figure 11: FEM – static analysis

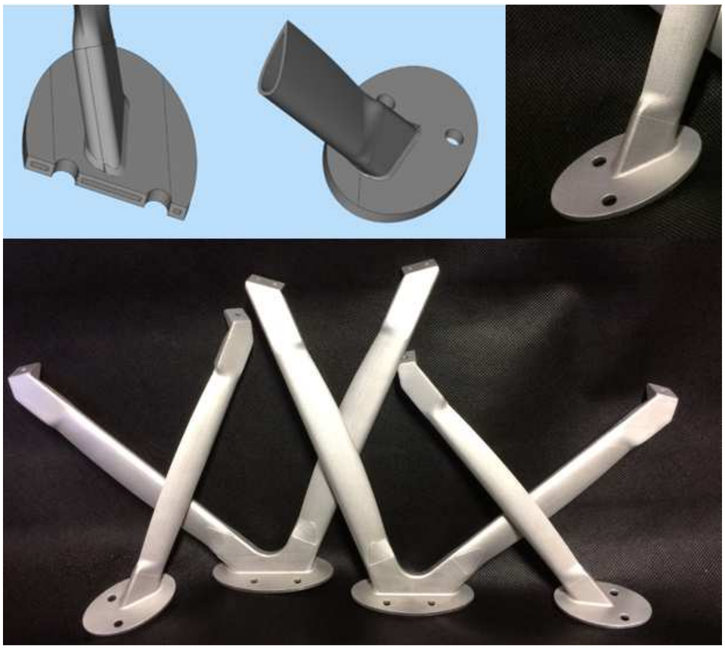

Figure 12: Final SLM engine mount legs

Finally, the third phase consists in printing the piece using the SLM technique. SLM is an AM technique developed to melt and fuse metallic powders via a high power-density laser. The principle of the SLM process starts with a building platform applied with very thin layers of metallic powders, which are completely melted later by the thermal energy induced by one or several laser beams. The cross-section area of the designed 3D part is built by selectively melting and re-solidifying metallic powders in each layer. The building platform is then lowered by a small distance and a new layer of powders are deposited and levelled by a re-coater. The laser beam(s) can be directed and focused through a computer-generated pattern by carefully designed scanner optics. Therefore, the powder particles can be selectively melted in the powder bed and form the shape of 3D objects according to the CAD design as shown in figure 10. The final results obtained from SLM production is shown in figure 12.

The main design change, with an important weight reduction, was the hollow leg design, with a 1.2mm of thickness all four legs has been emptied, exploiting the potential of SLM additive manufacture, without compromising structural stability and offering an internal cable routing from battery pack placed in the hull to the motors, via the main body and the inside of the legs).

To allow the easiest print design, the lower legs has been separated in two different pieces (four considering the whole symmetric geometry) to fit properly the 3D printer (plate dimension: 25cmx25cm height: 30cm); the printer used was a Print Sharp 250 from the Italian manufacturer Prima Additive [16]. The single rear leg has a weight of about 38.5g and the forward V shape legs has a weight of about 127g and with a final total engine mount weight of 550g.

5. Conclusions

In this document we have shown how the 3D printing technology allow to make the molds necessary for the lamination of carbon fiber RPAV airframe, in a completely autonomous way. In fact, it was not necessary to interface with an external supplier with an important time saving, in addition thanks to the use of PLA and topological optimization, more time and money has been saved during the process parameters setup phase.

The construction of the engine mount using SLM (Selective Laser Melting) allowed us to obtain high fidelity with the original drawings in the visible areas and a light structure thanks to the great freedom in design made possible by this technology. This was an important result to comply with a very light structure F4C competition rules and have an advantage in the competition regarding the aesthetics. Furthermore a significant time saving was achieved by making the complete engine truss in 4 item only.

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The contact author email is enrico.cestino@polito.it

7. Copyright Statement

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