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Additive Manufacturing Offers New Opportunities in UAV Research

Carlo Ferro[a]*, Roberto Grassi[a]*, Carlo Seclì[b]*, Paolo Maggiore[a] *

a Politecnico di Torino, DIMEAS, Corso Duca Degli Abruzzi 24, Torino 10129 Italy ,
b Altair Engineering srl, via Livorno 60 c/o Environment Park, Torino 10129 Italy

* * Corresponding authors. Tel.: +39.090.6858. E-mail address: carlo.ferro@polito.it, roberto.grassi@polito.it, carlo.secli@altair.com

Abstract

Multi-rotors vehicles have become a consolidated reality in modern aeronautical field. These small helicopters consist in a fuselage "hanged" under a set of fixed pitch propellers each powered by an electric motor. These vehicles have great potentials and research in this topic is increasing aimed to reduce the structure weight to maximize flight time, range and payload.
Multi rotor components represent a key challenge for 3D modeling, optimization and additive manufacturing: they mainly consist in complex shapes where the most important feature are robustness and lightweight. Usually produced in small series, for example, eight parts for a single prototype, they almost need to be able to interface different materials.
The work here presented shows the advanced research conducted in cooperation between Altair Engineering and Politecnico di Torino to develop vital components for the structure of a multi-rotor: they represent a challenge because the main need is to interface arms, consisting in carbon fiber tubes, with motor or frame, both made in 7075 Alloy.
The use of topology optimization techniques plays a key role to minimize the weight of the components and to improve the productivity of the machines. Moreover, Additive manufacturing (FDM with Sharebot NG) allows producing more parts in less time improving the cost effectiveness of the project. The process will be described from a simple characterization of the anisotropic properties of 3-D printed specimens to FEM analysis of the preliminary design of the component and to the optimization phase performed with Altair Optistruct code.
An important role is played from the Altair tool used for the preliminary design: Inspire. This tool is conceived to generate structural efficient concepts quickly and easily to obtain lighter designs and eliminate structural design problems and finally provide input files for 3-D printers.

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Keywords: multi rotor; 3dprinting; concept design; concepts; AM; FDM; Sharebot; Additive Manufacturing; Optimization

1. Main text

The flying drones, aircrafts that can fly autonomously (Unmanned Aerial Vehicle - UAV) or can be remote controlled (Remotely Piloted Vehicle - RPV), are now widely used and well established, although their use has so far been constrained by operational range due to their poor flight time.

Figure 1 Picture of a typical multi-rotor aircraft used for aerial photography

The multi rotor family, in versions quadra- exa- or multi-copters, depending on the number of propellers used, represents a class of aircraft with some similarity to helicopters where the lifting function is demanded to a rack of independent propellers driven each by its own electric motor. In this way, it combines the operating advantage of maintaining the position at zero speed (hover) with the addition of the possibility of fault tolerance features that benefit on the redundant lifting system which can survive to the failure of one rotor.
Currently these flying machines employ consolidated technological solutions and are only used for the transport of

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cameras and photographic equipment. These limitations mainly arise from their low operative range. The aircraft in research and development at Politecnico di Torino will exceed the inherent limitations imposed by the actual technology by introducing the use of the most advanced design techniques for optimizing the structure with the final goal to reduce its weight to the minimum.
Every action of weight reduction in a rotorcraft has the inherent goal to extend the range, the drone in study, named RecordRotor, will extend it beyond the limits by introducing new technological solutions in the power system which will lead to an increased ratio between power and weight while the optimization of the whole structure will give its contribution.
Additive Manufactured polymer components will play an important role in the prototype which will be designed at the upper boundary of the normative with a MTOW of 25 kg.

2. Additive Manufacturing

The selection of the additive manufacturing process has been taken to reduce the cost of the production of the prototypes, to increase the manufacturing speed and to control directly the process parameters influencing the mechanical properties of the part constructed. Moreover also the possibility to build yet a small series or pre-series of those part has been an advantage taken into account.

This technique has been used together with the free shape topological optimization. It will be described later that with these two technique consistent savings in mass are reachable with the same properties (stiffness, strength etc.)

2.1. Process description

Additive manufacturing technique (AM) is one of the most promising techniques to produce parts neglecting the prototype development phase, the cost of the pre series tooling and allowing the final user to have directly a prototype or a component that can be used yet few hours after the design phase.

Rapid prototyping matches the requirements of the new UAS research and industrial development for its ability to shortens product development time to have a faster building of flying parts to test.

Fused deposition Modeling (FDM) is one of the most used techniques in the AM since almost half of the machines that are introduced belongs to this category.

The overall process of the FDM starts from a CAD model exported to the CAM via a particular format: STL; this format triangulates the part introducing an approximation on splines, curves etc. The errors introduced are acceptable as long as they are under the accuracy level of the machine process($\approx$ 0.5mm)

The STL file is taken as input by the CAM (Repetier-Host or Quickslice®) and horizontally sliced in sections equal to the layer thickness selected (generally it varies from 0.1mm to 0.3mm). For each layer the software select the path of the nozzle to fill the part with stacks taking into account some process variables such as stack width, air gab between roads and stack angle on the xy plane.

In this technique a polymeric filament is semi-molted into an extruder and then deposited onto a platform through a nozzle that moves in the xy plane. When the material extruded solidifies it forms what is called the “road” or the raster. By depositing layer after layer these roads it is possible to build both internal and external geometries. In a layer the semi-molten material is deposited over the previous layer in such a way that the newly deposited material fused with the old one in a unique part. When the path is finished the entire platform moves vertically and the new layer is ready to be deposited over the old one. Since the process deposits roads in a plane it follows that the parts produced have an anisotropic behavior. A simple characterization has been established to evaluate the mechanical behavior of the parts produced with the Sharebot FDM machine using ABS (acrylonitrile butadiene styrene) filament.

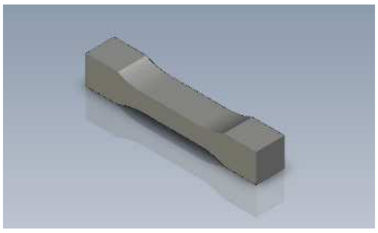
2.2. Characterization of the process

In order to design with topology optimization method data of the material are required. In literature several experimental analysis are available that investigates the mechanical properties and the quality [1] of ABS parts produced using a STRATASYS 1600 or 1650 FDM machines, but no recognized data have been found for Sharebot NG. In order to fulfill this vacancy a simple characterization with fixed process parameters have been done to evaluate the anisotropic material properties this material. Taking into account the information of the DOE performed in literature by [2,3,4] a machine parameter setting had been proposed in table.

Table 1 Machine parameters

Parameter Name	Value	UoM
layer height	0.2	mm
Infil	Rectilinear	---
Infil density	100%	---
Infil angle	45	°deg
Extruder temp	245	°C
Bed temp	95	°C
Deposition speed-Perimeters	30	mm/s
Deposition infil	60	mm/s

The specimen has been designed according to the ASTM standard for polymeric materials tensile characterization; the normative allows the researcher to perform a scaling of the design this option has been chosen to shorten printing time and to reduce raw material consumption



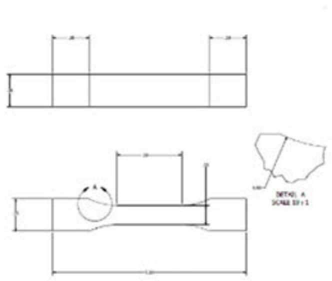


Figure 2 Micro Tensile Specimen 3D view and drawing

A benchmark of 3 micro tensile specimen have been produced for each job and two job were repeated with the same growth direction: one with the mayor axis of the specimen parallel to the z axis of the machine and the other with the specimen perpendicular to the z axis in the x direction. Twelve micro tensile specimen were produced and tested at traction using an MTS machine model Q-test 10 elite.

The data collected from the traction test are summarized in the table 2. As seeable there is an anisotropic behavior due to the manufacturing direction: the medium peak stress in the specimen build in the x direction was of 28.5 MPa versus a mean of 24.1 MPa for the specimens built vertically.

The specimen were linked to the machine perpendicular to the plane with the radius to avoid stress concentration on the contour fiber and rupture outside of the reduced cross section in the middle. It has been proved by the pre testing specimens and by literature [2] that linking the parts to the grips lead to false evaluation due to rupture in the connecting radius; connecting the specimen to the MTS machine with the plane perpendicular to the radius section has solved the problem preserving the reliability of the data collected

Table 2 Data collected from traction analysis

Name	Peak load [N]	Peak stress [MPa}	Displ at peak load [mm]	Secant stiffness [N/mm]	Elongation at rupture [%]
Batch 1 Z-1	636	24	2.184	291	5.7
Batch 1 Z-2	616	24	2.293	269	6.0
Batch 1 Z-3	578	22	1.89	306	5.0
Batch 2 Z-1	588	23	2.019	291	5.3
Batch 2 Z-2	692	27	2.512	275	6.6
Batch 2 Z-3	649	25	2.27	286	6.0
Batch 1 X-1	722	26	3.001	241	7.9
Batch 1 X-2	731	26	3.123	234	8.2
Batch 1 X-3	828	30	3.43	241	9.0
Batch 2 X-1	870	31	3.351	260	8.8
Batch 2 X-2	890	32	3.273	272	8.6
Batch 2 X-3	869	31	3.366	237	9.6

Below are presented the data collected during the testing phase for the vertical specimen and for the horizontal specimens. The first graph shows a good comparison between the different specimens that follows the same path increasing the load. There are some discrepancy on the rupture load that has got a spread of the 16% (from the 698 N of the batch 2 Z-2 to the 578 N of the batch 1 Z-3). The path described shows a classical elastoplastic trend with a large plastic zone and important deformation at rupture (up to 6.6% of elongation).

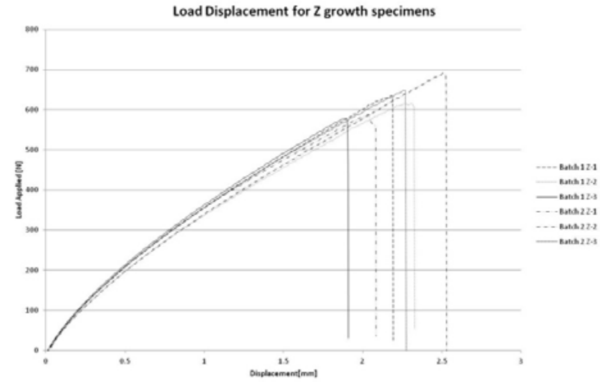


Figure 3 Load Applied vs Displacement for Z growth specimens

In the figure 4 it is possible to observe the trend regarding the horizontal built specimens. Here there is less uniformity between the different batch with sensible discrepancy on the ultimate load of the 18% (from 890 N of the Batch 2 X-2 to the 722 N of the batch 1 X-1). Also the trend during the elongation is not constant but varies due to the difference in the rupture path of the fiber of ABS during the test. However it varies from 7.9% to 9.6%.

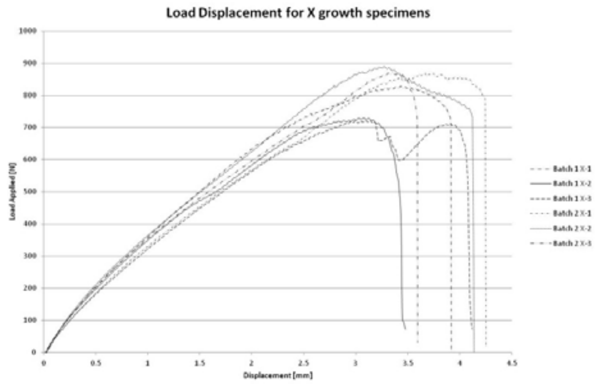


Figure 4 Load Applied vs Displacement for X growth specimens

As sustained in literature [3] the structure of a part fabricated with fused deposition modeling it's not different from a part built of reinforced carbon fiber. The better results from the X-grown direction specimens (890 N vs 698 N of maximum ultimate load) are because the individual roads that compose the specimen are significantly stronger in the axial direction than in the cross section where the fibers are simply glued.

However from this short characterization only the minimum performance for each axis will be taken out leaving for further analysis the improve of the performance. In this way there will be a safe design phase that will have improvement margins when a more specific characterization will be carried on.

3. Concept design using Solid Thinking Inspire

3.1. Description of the tool

The Altair Engineering's software SolidThinking Inspire, figure 5, enables design engineers, product designers to create and investigate structurally efficient concepts quickly and easily. Traditional structural simulations allow engineers to check if a design will support the required loads. Inspire enhances this process by generating a new material layout within a package space using the loads as an input. The software works with existing CAD tools to help design structural parts right the first time, reducing costs,

development time, material consumption, and product weight.

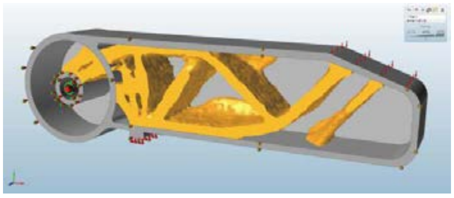


Figure 5 Solid Thinking Inspire example

Inspire is an up-front, concept design tool that was developed for design engineers and designers to enable users to design their products faster, smarter, and lighter. Given the package space and loading conditions for a design problem, Inspire quickly generates the ideal shape. This results in structurally efficient concept designs that you can use as a starting point for CAD.

Figure 6 Solid Thinking Inspire example

The objective of this program is to be used as concept design tool, before go through the Design+CAE step: design engineers can provide to analysts a first concept design that now is already optimized and validated. This approach will be the key point for the future because it will help saving weight, time and cost (Figure 7).

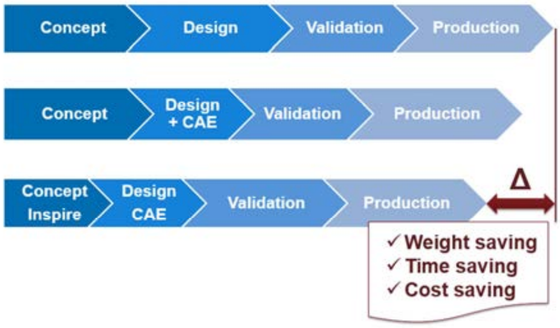


Figure 7 Different workstream using Inspire Tool

3.2. Work stream with Inspire

The work stream using the SolidThinking Inspire tool renewal the standard design process introducing new phase type and deleting others. Here below a standard stream type is presented showing the flow

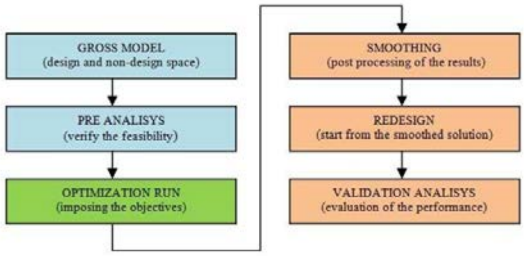


Figure 8 Stream of design

3.3. Activity description

The design process starts from the gross model; this model does not describe the shape of the part but contains just the information of the boundary dimension that the part can occupy and the interface that cannot be modified. Generally it's practice to divide this two components of the part to be designed into two separate parts, called the design and non-design space. Into the design there is the whole partition of the component that can be modified and reduced while in the non-design space there are the features that is mandatory to non change (interface with screws and carbon pipe in our case).

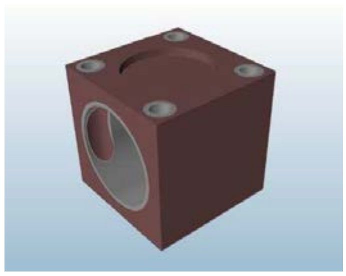


Figure 9 Design and Non-design space in gross mode

In the figure 9 it is evidenced as burgundy the design space and in grey the non design space. It’s important to point that the load and the constraints have to be putted only in the non design space otherwise their point of application would change along the optimization iterations. In this particular case the gross model described above coincides with the original model built in Aluminum Alloy 7075 for a weight of 34.5g.

After the design of the gross model boundary constrain, material properties and loads have to be imposed to the part. In this case the central cylinder has been fixed in all the six degrees of freedom (they represent the rigid link with the carbon pipe). The loads have been imposed in the screw holes for a total vertical force of 40 N (1.5 Mpa for each surface) and a torque of 3.3 Nm (825 Nmm for each screw). The material properties have been experimentally deducted in the previous section. An optimization run has been launched imposing the target of volume fraction reduction (minimum 30%) and the minimum level of the first ten modes greater than 250 Hz. The output of the optimization are presented in figure 10. After the optimization phase the output to the user is a rough part with a complex shape that need to be fitted into more simple shapes. In the case described above the optimization result for the structural optimization before and after the smoothing is shown in figure 10

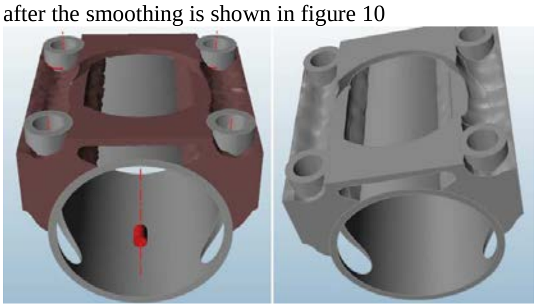


Figure 10 Optimization result pre and after smoothing

The algorithm used to smooth and trigger the surface is OS-Smooth by Altair and it is directly implemented inside Inspire interface so that it is easier to the designer to export the optimization results directly in the CAD for the re-design phase.

With this results the part has been redesigned adding material respect to the optimum to ease the manufacturing process via FDM. The upper part has filled up to the level of the interface to the motor with the to minimize the supports to be built in FDM (scrap part) and increase the strength of the part. The complete result had shown an increase off the weight of 3.0 grams up to 6.4 grams but it is still five times lighter than the original part constructed in aluminum 7075.

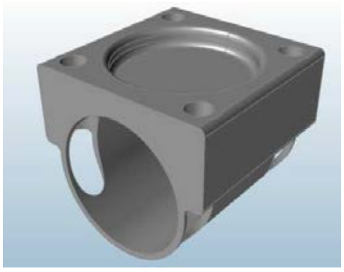


Figure 11 Re-designed part

With the new design in hand, it is mandatory to re-analyze the part to verify the compliance with the original constraint. In figure 12 are reported displacement and static stresses for the optimized version while in table 3 the modal frequencies are reported, which are well above the 250 Hz.

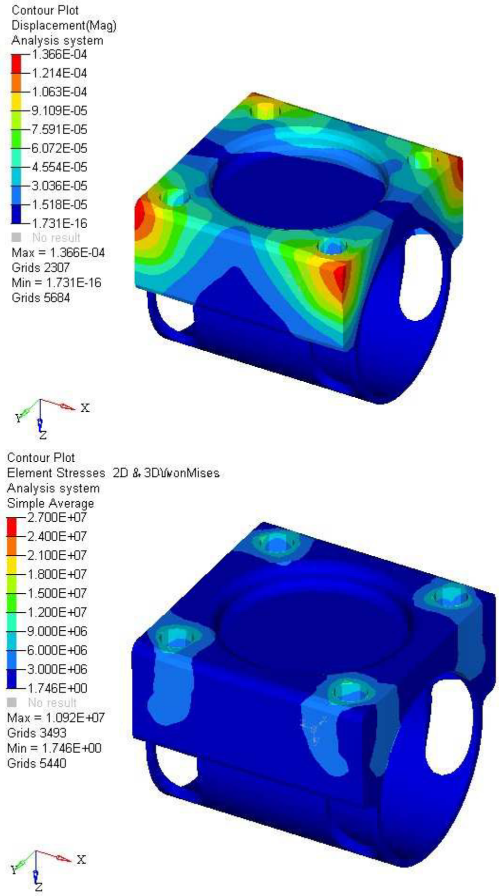


Figure 12 Dispalcement [m] and static stresses [Pa] for optimized design

N° mode	Frequency [Hz]
1	8.583641E+03
2	9.973915E+03
3	1.007774E+04
4	1.084295E+04
5	1.094334E+04
6	1.189299E+04
7	1.209179E+04
8	1.249866E+04

Table 3 Data collected from traction analysis

4. Prototype testing

After the conclusion of the design process, an experimental test has been carried to evaluate the behavior of the component constructed in FDM in a critical scenario. The safety factor introduced in the calculation above was of 1.5. A prototype of the part has been constructed and tested in the most critical situation: rupture of two of the four screws and shutdown of half of the motor of the UAS. In this situation the part has to resist to 80 N of load distributed on only two screws instead of four for at least 3 minutes to allow the UAV to a safe landing. This design philosophy, known as fail-safe, has been adopted for all the other critical structural parts.

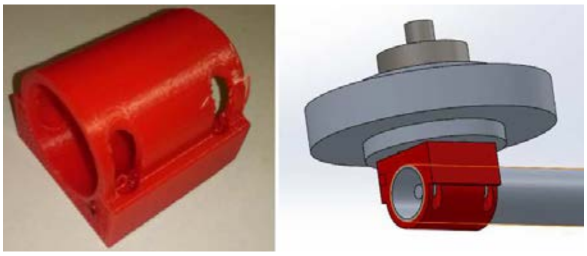


Figure 13 First prototype

Initial poor quality of the product is due to the difficulties in setting up the FDM technique for printing in low cross section areas while the solid regions of the component are compact and no surface flaw is visible.

The component was then finished by milling of the internal circular surface and the screw holes were drilled into the solid. Sequent generation of prototypes will be designed and produced including the holes and a more accurate finishing will be given to the coupling surface thus not requiring any more milling treatment. The component was then assembled on a static test bench comprising a mock up of the motor and the CF tube, it was then suspended and loaded with sample weights, overcoming the critical test with no visible damages.

Figure 14 Experimental test

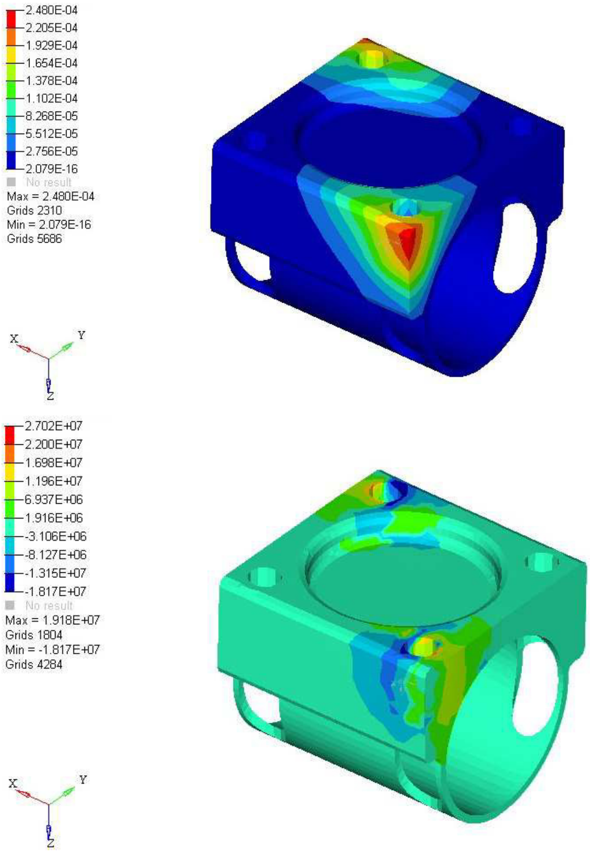


Figure 15 Displacement [m] and static stresses [Pa] analysis for the experimental test case

5. Conclusion

The outstanding potentials of FDM printing have been disclosed in this paper, it has been demonstrated that with an adequate scientific methodology and with the support of innovative design tools it is possible to construct high performance optimized components for the aerospace industry. The potential application has mainly been identified in an innovative UAV, which will compete for a world record. In the next papers, we will analyze the necessary steps to improve design and qualification methodology up to an aerospace industry grade

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