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The commissioning of a hybrid multi-material 3D printer

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Abstract: Additive Manufacturing (AM) has rapidly become an important technology in both research and industry. This development has allowed the evolution of 3D printers which are able to print complex geometries at low costs and faster than traditional methods. Despite this, most of these printers are either only for using one material or one technology. This limits a lot its use in different sectors such as aeronautics, automotive or health, because multi-material prototypes are needed. For example, surgeons need surgical planning prototypes for preoperative planning. These 3D printed prototypes have mainly been manufactured using just one technology. As a result, the prototypes have some main limitations: (1) do not actually mimic the anatomical structures of the human body, (2) high costs specially for Material Jetting and Powder Bed Fusion AM technologies. Therefore, the aim of present manuscript is the design, development, and commissioning of a hybrid multi-material 3D printer.

Keywords: Multi-material, 3D printing, Hybrid, Surgical planning prototypes, Health.

1. Introduction

Additive Manufacturing (AM), the industrial version of 3D printing, can be defined as a revolutionary technology in which objects are manufactured with one or different materials which are deposited layer-upon-layer along the geometry shape until it grows in height to obtain the model. This process is the opposite of subtractive manufacturing, in which the geometry is obtained by removing material from a solid block. Within the AM technologies, ISO/ASTM 52900 Standard classifies all technologies in seven categories [1]: binder jetting, direct energy deposition, material extrusion (includes Fused Filament Fabrication (FFF) and Direct Ink Writing (DIW) also known as Robocasting), material jetting, powder bed fusion (includes selective laser sintering (SLS) and Multi Jet Fusion HP), sheet lamination and vat photopolymerisation (includes stereolithography (SLA) and DLP/LCD systems).

AM is starting to bloom up and is applied in different sectors such aeronautics, automotive and health. Regarding the latter sector, AM has been used in the manufacture of prostheses, implants, scaffolds, surgical guides, surgical planning prototypes, etc. For example, the manufacture of 3D models has been mainly done with just one AM technology or with only one material, normally hard, which do not actually represent the anatomical structure of the human body [2,3]. Additionally, the moulding technique has also been used, in which the negative of the prototype is 3D printed, and then a soft material is cast inside the mould [3-6].

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The combination of two AM technologies has already been studied in other sectors. For example, Fieber et al. [7] manufactured energy storage devices using FDM and DIW. This new approach offers an alternative fabrication process for applications with irregular volume/shape and mass-customization requirements. On the other hand, Hinton [8] produced a functional 555-timer circuit on planar and 3D ceramic alumina substrates that were made using the hybrid manufacturing platform to demonstrate the feasibility of hybrid 3D printers.

Therefore, the aim of the present paper is to introduce the design, development, and commissioning of a hybrid-multi material 3D printer. For that, a brief explanation about the two technologies, DIW and FFF, used in this 3D printer is given. Then, the different parts of the machine are explained as well as the different parameters for a good printing. And finally, several examples are shown to validate the correct operation of the machine.

2. Two powerful AM technologies merged into one

2.1. The technologies

FFF and DIW are, by themselves, two innovative and powerful technologies that have an important role in the 3D printing revolution. However, it can still go further with the fusion of both. It is about developing a new machine with the best of each to go deeper and be capable of manufacturing realistic and inexpensive surgical planning prototypes among many other possibilities. Research on multi-material 3Dprinting using these technologies is a must, considering the high cost of other options (e.g. Material Jetting and Powder Bed Fusion AM technologies), and a first classification about them can be found at [9].

FFF is a printing process based on the extrusion of a continuous filament of a thermoplastic material that melts to be deposited. DIW is also an extrusion-based method but it dispenses the material in a viscous phase, called ink or paste. The process is based on the deposition layer upon layer of this ink. It has some printable requirements to grow in height, especially about its viscosity.

2.2. Materials

FFF technology uses filament materials like polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polyvinyl alcohol (PVA) and thermoplastic elastomer or polyurethane (TPE/TPU). Each of them has its own characteristics.

PLA is a thermoplastic polyester and is probably the most widely used material due to its low process temperature, and ABS is a thermoplastic polymer with a high resistance to the impact. On the other hand, PVA is commonly used as a support material due to its water-soluble property that facilitates the removal, especially with complex geometries. And finally, TPE and TPU have an important advantage, despite their printing difficulties, which are their flexibility and the wide range of Shore hardness grade available.

For surgical planning prototype’s purpose, each material will have a specific use. PLA is used for anatomical structures considered “rigid” like bones or cartilages, but other softer structures can be also represented by PLA if necessary, as for example blood vessels that need to keep stable in the prototype to get a good visualisation. In the case shown in figure 1, vertebras and blood vessels are materialised with PLA, PVA is used for support and a soft TPE for the tumour. This combination seems optimal, not only to obtain a specific hardness depending on the organ tissue, but also to make the most possible realistic prototype.

Regarding to DIW, it is a technology that is used for the 3D printing of silicones and other liquids as hydrogels. For example, Tan et al. [10] developed PVA/PHY hydrogels which were 3D printed for soft tissue phantoms. A similar composite was synthetized by Forte et al. [11] in order to produce a soft brain phantom. These last materials, even though its ability to mimic living tissue, must ensure self-consolidation in a 3D printing process: be stable in shape to guarantee a good layer deposition and therefore to grow in height without auto-collapse.

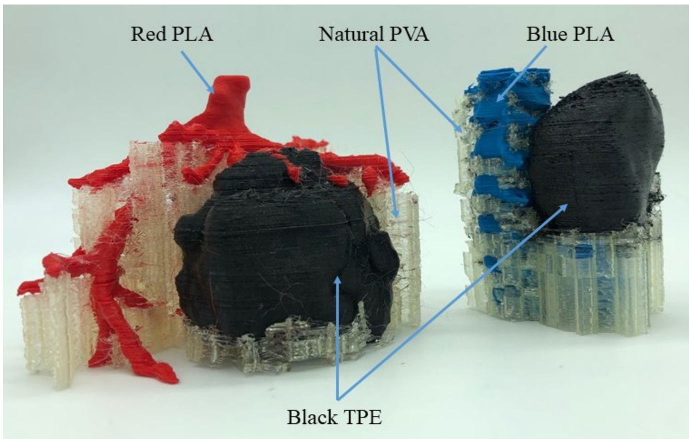

Figure 1. Multi-material part of a liver fibrosis (left) and a neuroblastoma (right) prototype.

3. Hybrid Multi-Material 3D printer

3.1. Introduction
The required machine with two technologies offers much more than this. It also has the possibility to print with different FFF's filaments due to its interchangeable tool. It is possible to mix colours and/or materials on demand in a single printing process. Figure 2 shows the machine and its main parts.

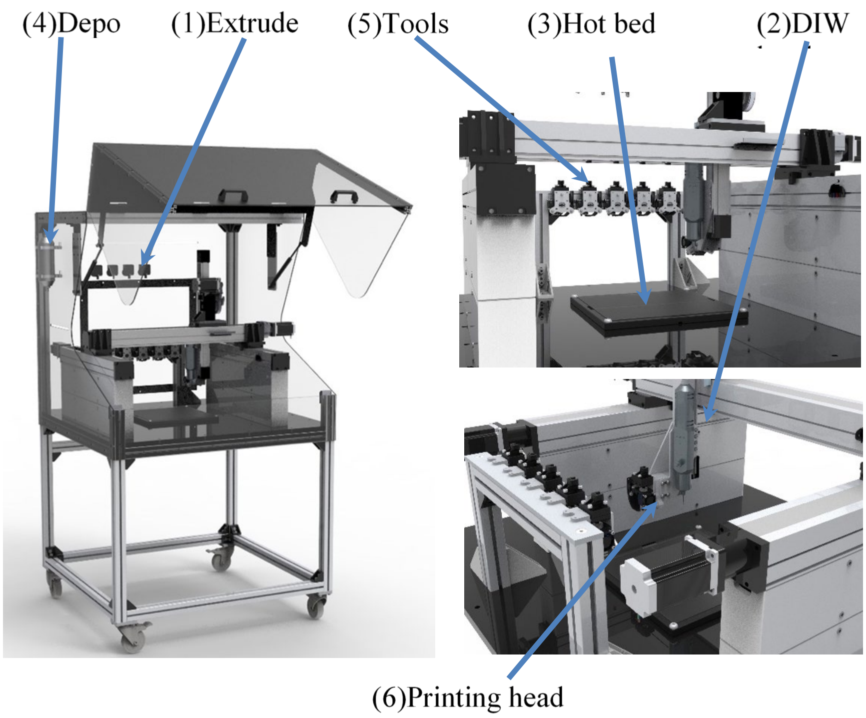

Figure 2. Hybrid multi-materials 3D printer parts.

For the surgical planning prototypes different volumes are needed. The biggest one would be for the printing of a liver which requires around 550 mL depending on the subject's anatomy. This determines the machine's need for a large deposit (4) for DIW's materials with around 600 mL of capacity. Consequently, it requires a large printing volume of 18 L (300 mm x 300 mm x 200 mm (x,y,z).

The bedplate is heated (3) because most FFF filaments need it to prevent shrinkage in the biggest models and ensure adherence of the base. The printing volume is also enclosed to keep the temperature stable and speed up the heating process.

The machine has a print-head (6) that is based with the interchangeable tool selected (5) (FFF's head) and the DIW's head (2).

For the FFF technology, the 3D printer has a rack with 3 extruders (1) and another rack with 3 tools (5). In the first rack, filaments are extruded through the bowdens to the tools, In the second rack, filaments reach around 230 ºC and fuse along the hotend. Tools in this rack can be interchanged to the print-head by a key lock system located at the end of the vertical axis. One of the tools is adapted to incorporate a probe, to perform a level mapping of the bedplate that allows to compensate Z height as if the system was ideally flat. FFF filaments, specially PVA, have storage requirements and are stored in an insulated box to protect them from moisture.

The DIW technology print-head (2) is performed using a standard system based on a progressive cavity pump that can work with a wide range of viscosities. Among the materials used for this technology, there are photocurable silicones that need an UV light to cure (see figure 3). So, there is also a system to cure the silicone while it is being deposited, fixed to the DIW print-head. It is based on a UV Led Head Unit with the option of adding one more led to cure from different positions.

Figure 3. Light Curing system with two UV-Led's.

3.2. Parameters

There are different characteristics and parameters related to the hybrid multi-material printer.

- Mechanical parts: the printer is based on Cartesian coordinates that is made up with one linear guide for X and Z axis and two linear guides for Y axis in a gantry configuration. For this printer, the Z carriage is fixed to its linear guide. Therefore, it is the whole Z linear motion system that moves with both FFF and DIW print-heads fixed on it at the lowest point. These linear units are enclosed to prevent dust from entering and controlled by stepper motors.
- Speed parameters: these parameters are defined by the material's manufacturer with an interval. However, the speed is not a fixed parameter, and the user will adapt it in the program according to the model's geometry. Usually, the slower the printing speed, the more accurate the part will be. In addition, it is commonly slowed down during the first layers to improve the adhesion to the bedplate.
- Temperature parameters: there are three different aspects referring to temperature.
  i) Hotend temperature is also defined by the material's manufacturer with an interval and the established value will depend mainly on the speed. The faster it is printed, the higher the temperature should be. The maximum temperature is 280 ºC.
  ii) The hot bed is not always turned on, it depends on the material and defined by the material's manufacturer. The maximum temperature of the hot bed is 100 ºC. However, with

a multi-material printer it is important to pay attention to all the materials in contact with the base, especially with silicones because it would increase the material's viscosity jeopardizing printing's success.
iii) Room temperature should be around 20/30 ºC and must not exceed 60 ºC as components may be damaged. As there is no room temperature control it will depend on the other components' usage-temperature and the period that the machine is closed.

- Resolution parameters: it is mainly determined by the layer height. However, it will have consequences also in the printing time. For example, with little layer height, higher resolution and longer printing time. The average layer height recommended is between 0.1 and 0.25 mm.
- Print-Head parameters: The FFF print-heads are interchangeable. FFF tools have a resting position whereas the DIW print-head is always fixed in the Z linear unit. When DIW technology is printing all FFF tools are resting. With this FFF interchangeable tool head less weight is carried, and the likelihood of motion system problems decreases. Additionally, as the tools, both FFF and DIW, are in different places of the print-head and all of them share the same Z-axis system, they are referenced one to the others with an offset system calibration. It is an automatic compensation of the different tools' positions. See figure 4.
- Curing parameters: the curing system incorporated is adaptable to different photocurable materials with a wavelength of 365 nm and an irradiance range from 4000 to 14000 nW/cm depending on the distance. Therefore, the curing system has been designed with adjustable heights. For instance, if the distance decreases, the irradiance increases. When using this system, it is important to use a UV-protected tip for the silicone's head to avoid curing the silicon inside the tip which would clog the system.

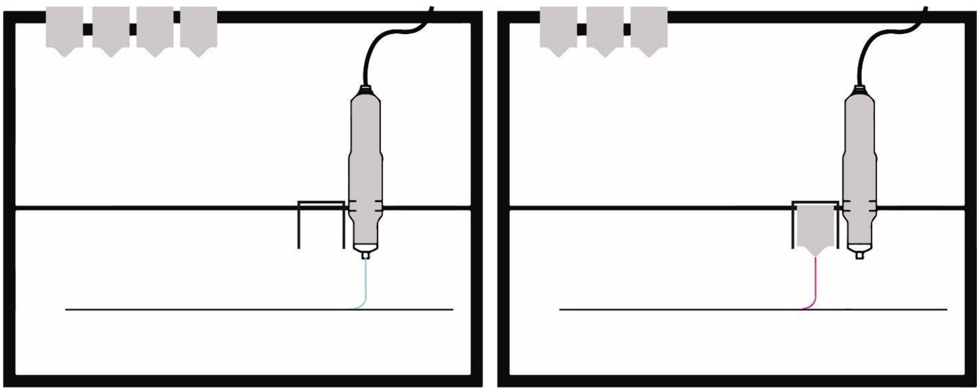

Figure 4. Tools display when printing with DIW (left) and FFF(right).

4. Demonstrators and results

It all started with nothing but uncertainties and after the machine was manufactured and configured, results began to emerge. There were different main objectives that results in the following:

- *Prove the functionality of the tool changer and improve it:* First thing to accomplish the objectives was to experiment with the tool changer. After different calibrations, tests and improvements, reliability was achieved. A complete real-scale model requires nearly three thousand tool's changes so a printing failure due to the tool changer was not an option.
- *3D print for a long period of time:* Long 3D printing periods were also tested and the longest print was about 100 hours. All components had good behaviour and the machine has proved to be autonomous during the whole printing process. See figure 5.

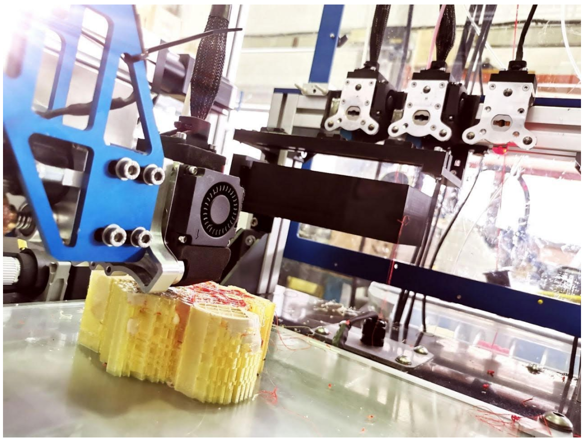

Figure 5. Perspective of the hybrid multi-material 3D printer at work.

- *3D print complex geometries with different materials:* Besides, there are different models, provided by Hospital Sant Joan de Déu i Barcelona (HSJD), that were tested. First the simple ones, with just one or two materials and 3d printing them on a smaller scale. Once they were obtained with good quality, more complex models were programmed to be 3D printed, as for example models with at least 3 different materials. Geometry itself was also a challenge: for example, a tumour in a model had 3 shells of TPE but the infill was with PVA, to remove it and obtain a softer tumour. See figure 6.

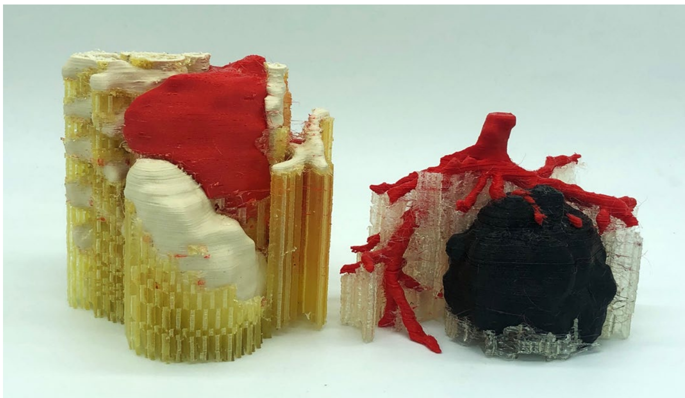

Figure 6. Surgical planning demonstrators.

- *Prove the compatibility of FFF's materials with DIW's materials:* Another big step is the compatibility of both technology's materials. The 3D model has some geometrical requirements that in FFF are commonly known such as cantilevers and detail's dimensions among others, but in DIW these are much more accentuated since they are not having support material and the printed liquid is not completely hard after the deposition. In addition, DIW's design must take into consideration that the liquid has a worst adhesion and will need slower speed to deposit the material all the way through sharp curves. Printing a simulation of a tracheal stent, to ensure the right height and to reduce possible inclination of the silicone's structure, a support structure was designed with FFF. The problem was that DIW's materials have temperature requirements and cannot be in touch with the hot bed even though it is necessary for FFF technology because it improves the adhesion to the printing base. This requirement means that the bed must be hot, but silicone should not be in touch with it. Thanks to the technology's combination it can be solved by adding a base and the internal structure printed with FFF, as it can be seen in figure 7.

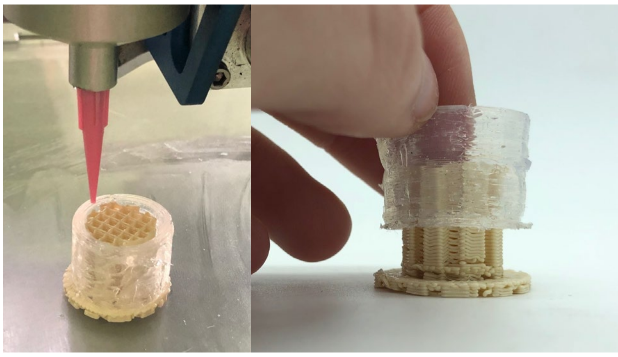

Figure 7. Printing demonstrator with silicone and PLA.

- *Establish a workflow:* To obtain a prototype there is an established workflow process that starts at the hospital, where the surgeon demands it. Next step is to obtain the Digital Imaging and Communication On Medicine (DICOM) by some scanners (CT, MRI) and after, the image segmentation of the model. Then the model is imported to a slicer software (Simplify3D in this case), with a stl format where all the printing parameters are defined, e.g., the layer height, speeds, infill, supports generation and temperatures, among others. This tool allows the user to previsualize the model as it will be 3D printed and change once and again whatever that is needed until the final version. Finally, it generates the GCode: it is the recompilation of all the orders, with the already established parameters, that the machine should execute. Once the model is printed, the last step is to remove the supports. In the following example, as supports are made with PVA, the model is submerged in water and after a while, the supports have dissolved. Now, it is ready to be taken to the hospital for the surgeon to help with the surgery planning.

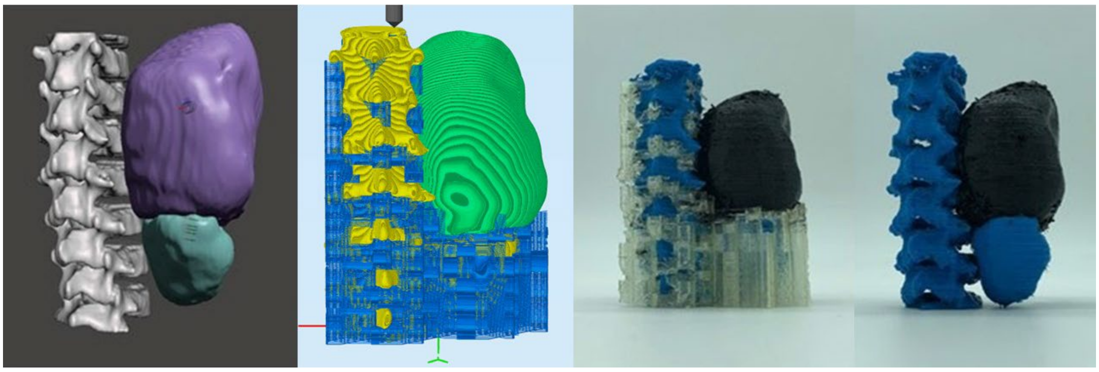

Figure 8. Workflow to manufacture a surgical planning prototype.

- *Establish a simple but effective supply chain with the hospital:* This final objective has become one of the most challenging (see figure 8). A good period time orientation would be about two or three days between the prototype being demanded and manufactured. With an interchangeable-tool system, printings require more time. Therefore, to reduce the time, printing parameters must be modified, layer height and/or printing speed must be increased or also less infill determined. All this contributes to deteriorate the printing quality of the model. The supply chain is simple, it is just between the hospital and the manufacturer but, as the printing process requires long periods, time effectiveness must be improved.

5. Conclusions
Even though there are other manufacturing ways, this challenge was important to demonstrate that it is a low-cost-effective technology. Additionally, it offers an added value as different colours, materials and different Shore hardness parts can be accomplished without using moulds.

From the start to now, different improvements have been accomplished. For example, the hybrid multi-material 3D printer has proved to be autonomous and functional for a long time-use. Its main drawback is the printing period. Thus, time and quality must be balanced to obtain parts not only as fast as possible, but also well-printed. As the geometry of the models is complex, it is completely necessary to use one tool for PVA's supports. Its ease to remove is completely helpful and speeds up the workflow's process.

For the moment, its functionality in surgical planning prototypes has been proved, especially for the surgeon to visualize the case and take decisions, and more multi-material prototypes will continue to be developed and manufactured. This disruptive 3D printer is the perfect tool for researchers to go further on multi-material AM, an open field. Investigating what this hybrid multi-material 3D printer can offer is not only an opportunity for the AM medical sector but also for other different AM sectors.

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