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Development of a multi-material 3D printing system with integrated post-production processes

Dissertação para obtenção do Grau de Mestre em Engenharia de Materiais

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Desenvolvimento de um sistema de impressão 3D de múltiplos materiais com processos de pós-produção integrados

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Abstract

This thesis main objective is to integrate 3D printing techniques with a post-processing method in a singular system. The idea is to use an existing 3D printer as the base structure, and then integrate an independent equipment for extrusion and spraying, as well as a laser system resulting in a multi-material 3D printing system with integrated post-production procedures.

The first task consisted in the substitution and suitability of the entire electronics, followed by the ability to print a viscous material by extrusion and this was tested by defining a range of parameters for which it is possible to obtain the desired design of the 3D printed part. With the preliminary tests accomplished it was verified the need for some adjustments, for example, an inclusion of a heating plate on the printing surface. This equipment gives an extrusion/spray ability to the 3D printer, so that it can be used with different material and/or viscosities. The next step was finding a solution for the coupling of the “add-on” type laser to perform the post-processing as a sintering and / or crosslink source. After installation of all components came the operation test and finishing, such as introduction of laser radiation protection panels, compressed air inlets, extruder / spray control source, etc.

The last part of this thesis was to assess the functionality of the full system and test the printing parameters: for the extrusion were: first layer height, rotation speed, print speed, density, layer height, software’s nozzle diameter, leaning capacity, double wall support; for the spray: dispensing time, dispenser exit width, dispensing height; and for the laser: manual focus and power.

Resumo

Esta tese tem objetivo principal a integração de diversas técnicas de impressão 3D com um método de pós-processamento num sistema único. Para isso partiu-se de impressora 3D existente nomeadamente aproveitou-se a sua estrutura base e depois integrou-se a componente de extrusão e pulverização e acoplamento de um laser, resultando num sistema de impressão 3D multifuncional.

A primeira tarefa consistiu na substituição e adequação de toda a eletrónica, na tarefa seguinte testou-se a capacidade de impressão de um material viscoso por extrusão, tendo-se definido a gama de parâmetros para os quais é possível obter o desenho pretendido da peça impressa. Com a realização dos testes preliminares verificou-se ser necessário alguns ajustes como por exemplo a inclusão de uma placa de aquecimento na superfície de impressão. Este equipamento confere à impressora 3D uma versatilidade de viscosidade e/ou materiais na extrusão / pulverização. O próximo passo foi encontrar uma solução para acoplar o laser tipo "add-on" para efetuar o pós-processamento como uma fonte de sinterização e / ou crosslink. Após instalação de todos os componentes seguiu-se o teste de funcionando e acabamentos tais como introdução de painéis de proteção à radiação do laser, entradas de ar comprimido, fonte de controlo da extrusora/spray, etc.

A última parte desta tese consistiu em avaliar a funcionalidade do sistema completo e teste dos parâmetros de impressão: para a extrusora - altura da primeira camada, velocidade de rotação, velocidade de movimentação, densidade, altura da camada, diâmetro do bocal no software, capacidade de inclinação, suporte de parede dupla; para o spray - tempo de dispersão, largura de saída do dispensador, altura de dispersão; e para o laser - foco manual e potência.

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List of acronyms

- 3D – Three Dimensions
- AM – Additive Manufacturing
- RP – Rapid Prototyping
- CAD – Computer Aided Design
- SLS – Selective Laser Sintering
- FDM – Fused Deposition Modeling
- SLA – Stereolithography
- UV – Ultra-Violet
- DIW – Direct Ink Writing
- RepRap – Replicating Rapid Prototyper
- LCD – Liquid Crystal Display
- SD Card – Secure Digital Card
- FLH – First Layer Height
- RS – Rotation Speed
- PS – Print Speed
- V – Volts
- Mm – Millimeters
- Mm/s – Millimeters per second
- LH – Layer Height
- MDF – Medium Density Fiber

1. Introduction

A generic overview of the 3D printing technologies available are presented with a short description of what is considered additive manufacturing, and a summary of the state of the art of 3D printing technologies and their post-production processes as well as some applications.

1.1. Additive manufacturing

Additive manufacturing (AM) is the formal term given to rapid prototyping (RP) that is commonly named as 3D Printing. This technology is based on the creation of a certain model, generated by a 3D Computer-Aided Design (3D CAD) system, that can be fabricated directly without the need for process planning. Thus, AM technology as definitely simplified the process of producing complex 3D objects directly from CAD data. Other manufacturing processes usually require a detailed analysis of the parts geometry, such as the order in which different features can be manufactured, what tools and processes must be used, and what additional fixtures may be needed to complete the parts.

The way AM works is that parts are manufactured by adding a layer of material on top of the previous layer, considering that each layer is a thin cross-section of the 3D model exported from the original 3D CAD file. That is, each layer must have a minimal thickness (depending on the technology used) to obtain a replica of the original design. The thinner each layer is, the more detailed the final part will be. The great difference in AM machines is the material that can be processed, how the layers are created, and how they are bonded to each other. This will determine factors like the accuracy of the final part, material properties as well as mechanical properties, the fabrication time, and the need for post-processing, the size of the AM machine and the costs of the whole process.[1]

1.2. 3D printing technologies

The most common 3D printing methods are melting or softening materials in Selective Laser Sintering (SLS) and Fused Deposition Modeling (FDM). Another method is curing a photo reactive resin with an UV laser or another similar power source - Stereolithography (SLA) or even DIW, Direct Ink Writing where viscous material is extruded

Fused Deposition Modeling technology consists on using a plastic filament or metal wire that is forced into a nozzle extruder that is heated until the melting point of the material is reached. At the same time, this nozzle is moved in a horizontal plane as well as in a vertical motion (figure 1). The object is formed by the deposition of the material on a previous layer that has been hardened due to the cooling of a fan pointed directly at the print zone. Nowadays, this technology is the most used since it is the easiest to work with, the most affordable and most of the brands are using it with an open source principle. Also the consumables are the cheaper from all the other technologies.[2][3]

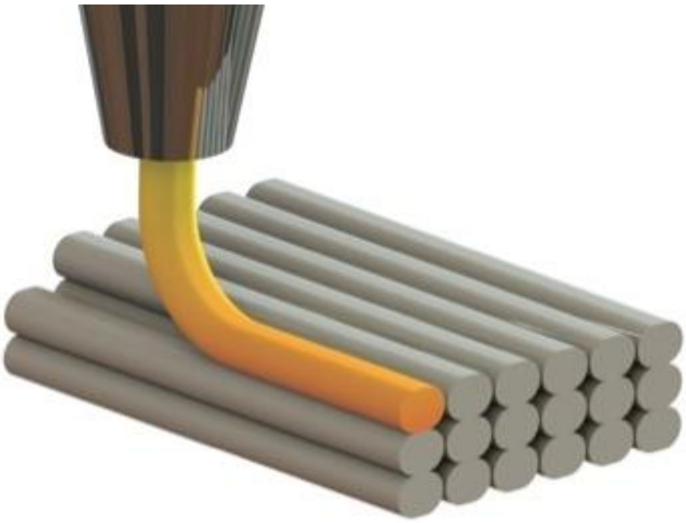


Figure 1 - Demonstration of how FDM technology works. [4]

Selective Laser Sintering uses a high-power laser to sinter small particles of plastic, metal, ceramic or glass powder into the desired 3D object. The powder is spread evenly across the bed and then the laser scans the layer after wish the bed lowers and a new layer of powder is applied on top. A distinct advantage in this technology is the fact that all used powder remained on the print bed volume acts as a support structure for the 3D print itself.[5]

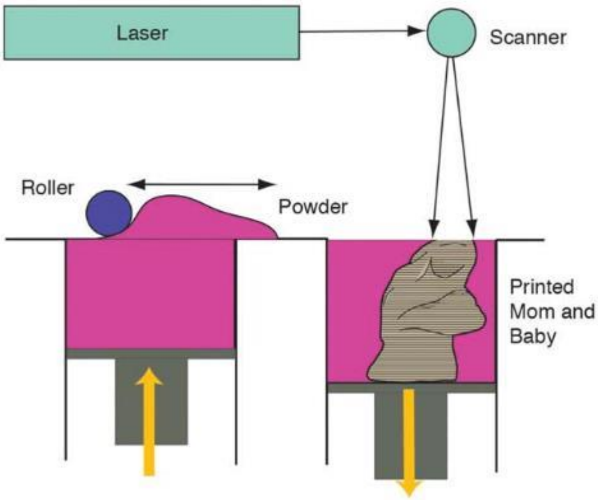


Figure 2 - Demonstration on how SLS technology works. [6]

As for Stereolithography, this technology uses a vessel with ultraviolet curable resin that is photopolymerized by an UV laser. Each layer the laser scans, the resin will harden and the object is formed layer by layer, but since the object is surrounded by liquid, is very important that the first layer adheres well to the bed.[7]

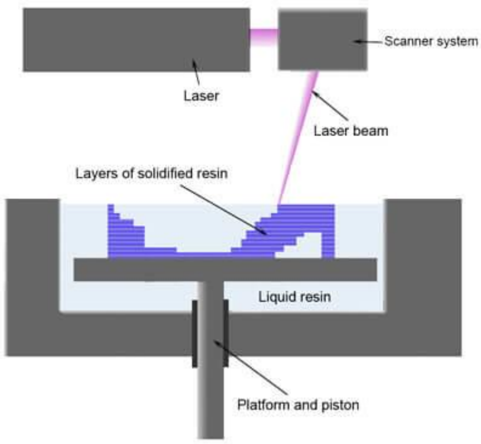


Figure 3 - Demonstration on how SLA technology works. [8]

Direct ink writing (figure 4) is a layer-by-layer assembly technique that has been used to fabricate constructs using materials including polymeric, sol–gel, and ceramic inks. The technique can be used to build scaffold structures designed by a computer. Scaffold architecture can thus be optimized to achieve the desired mechanical response, accelerate the bone regeneration process, and guide the formation of bone with the appropriate anatomical cortical–trabecular structure. Achieving these goals, however, requires a process able to print a wide range of materials with custom made compositions and increased precision. In the design of such a process the formulation of concentrated inks with the optimal rheological properties is crucial. Several direct ink writing techniques have been introduced that are capable of patterning materials in three dimensions. They can be divided into filamentary-based approaches, such as robocasting (or robotic deposition), micro-pen writing, and fused deposition, and droplet-based approaches, such as ink-jet printing and hot-melt printing.[9][10]

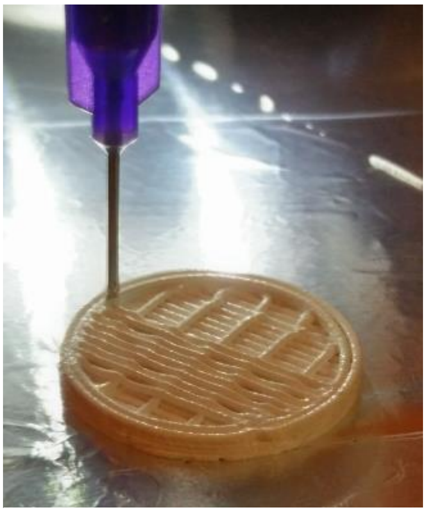


Figure 4 - Direct Ink Writing example.

1.3. Post-production procedures

All 3D printing technologies referred before need a basic post-production procedure such as cleaning the print (getting any imperfection or support). In the case of FDM, it may need a cover of prime and then sand it until smooth, so that it could be painted afterwards. SLA may need to be metalized or UV radiation surface treatment or even wet sanding. For SLS process, after the cleanup, the object may appear porous and therefore the part may need to be annealed, or even other manufacturing processing such as machining some parts. In terms of DIW the part typically needs to be dried or sintered in the oven to remove the binder.

1.4. Applications

Applications for 3D printing are endless and it can be used in the fields of medicine, aerospace, automotive, jewelry, art or even food. The ability to print whatever design you desire makes the technology perfect for everyday items in our houses, on the streets, at transportations, even for ourselves. For example, with the use of a 3D scanner you can reproduce any limb in case of amputee, in a matter of days it can be 3D print a perfect scale and shape prosthetic. Even better, with the most recent developments, it will be possible soon to replicate any organ on our bodies and this way ending the need for organ donors.

Another very remarkable application is 3D bioprinting bones, from a full bone to a small segment. The only barrier that has been found is biocompatibility and the adequate materials. The optimal technology for this would be the SLS of ceramics but there are still too many impurities and only some non-biocompatibility materials for this process, also, it is still extremely expensive to have such system. So, an alternative to that is the use of ceramics in a liquid state, and there is not such a system available to use for researching new materials and processes. Therefore, the necessity came to create such system.

1.5. Objective of the thesis

As mentioned previously, the need to have a 3D printing system able to produce ceramic pieces from a ceramic paste was the main motivation of this thesis' work. Moreover, it was also intended to have a multi-material and multi-process 3D printing to enhance versatility envisaging research proposes. Therefore, at the end of the work a prototype system with the Direct Ink Writing Technology, able to produce laboratory scale pieces of ceramics, polymers, or low melting point metals is expected. The possibility to do curing processing while the layers are printing is an add functionality compared to most state of the art printers.

2. Materials and methods

In this thesis, the starting point was a “Reprap Prusa i3” (figure 5 – a) that is known worldwide as the DIY (do it yourself) 3D printer and that has a lot of documentation on how to change or upgrade it. But in our case the idea was to have a good strong base and unfortunately the Prusa i3 tends to gain some clearance over time that compromises the print quality. Another big issue is that this 3D printer if fully open, it has a vertical wall for the X and Z axis and the base for the Y axis wish does not allow to build an enclose on the printer itself. So, for this reason we had to follow another route and find another 3D system that would accommodate all our needs and we decided to go for a 3D printer that was already on the lab. Unfortunately, this 3D printer never worked properly but it had both the strong structure and the best frame to add the enclosure plates.

The printer that was used is a “Leapfrog Creatr 3D 2014” (figure 5 – b), it had a lot of issues since it was bought. It had several problems with the mainboard, which ended up being replaced a couple of times but never truly fixed. Another big issue was the heated bed. Usually there were some problems when heating the surface that needs almost an hour to be heated up to 80 ºC (in a normal printer this takes about 5 minutes maximum). Also, there were some problems in the Y axis, it was too noisy when moving and not precise.

Considering all the above it was decided to start to replace the electronics, the mainboard was removed and replaced by a Ramps 1.4 (figure 5 – c), a very well-known and tested mainboard. This new board has a feature that the original from the Leapfrog did not have, the ability to connect an LCD with a SD card reader enabling the user to control the printer without the need of a computer permanently connected, thus, giving a lot more freedom to any user to prepare the files previously or use any computer available.

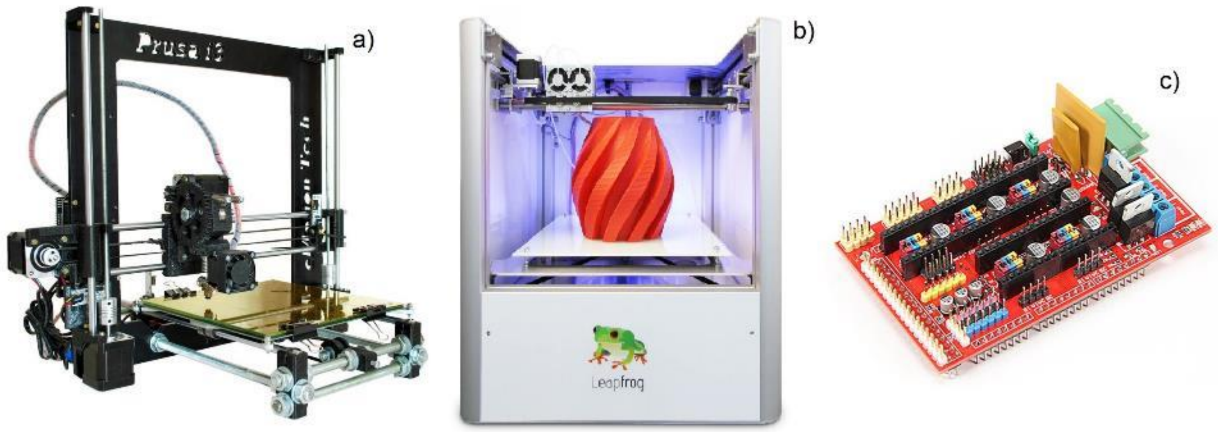


Figure 5 - a) Prusa i3 [11]; b) Leapfrog Creatr 3D 2014 [12]; c) Ramps 1.4 [13].

The next components to be replaced were the end stops that control the axis lengths. The one on the X axis was a simple mechanical switch that was not trigging properly on the Z axis and a capacitive sensor that had some issues to communicate with the main board, were also replaced. So, all the end stops were replaced by new mechanical switches. On the Y and Z axis, a length regulator was designed just to have some clearance in case there was something that might need more space.

The reason the Y axis was not working properly was due to the bearings of the X axis with the Y axis that weren't properly fixed. They were too tight, and the bearing decenters from the rod and was getting stuck. So, centering the rod and a little bit of lubricant lead it to slide perfectly.

The power supply was also replaced. Originally it had a 24 V due to the requirements of the very large heated bed and since it was no longer needed, a 12 V power source was enough to power supply electronics and motors. Final check was done to verify the proper connection and working of all the motors, the end stops and a first simple firmware for the new main board to test the workability of all components.

As the printer uses a syringe, there was the need to do a support for compressing the syringes plunger while printing - first the supports were though, then designed and printed in a regular extruder on a FDM 3D printer. The support contains several separated parts that were put together in order to push the plunger while holding the syringe. The nuts were fitted in a 3D part where the top of plunger is locked in and so by rotating the motor it will go down or up according to the motors direction (figure 6).

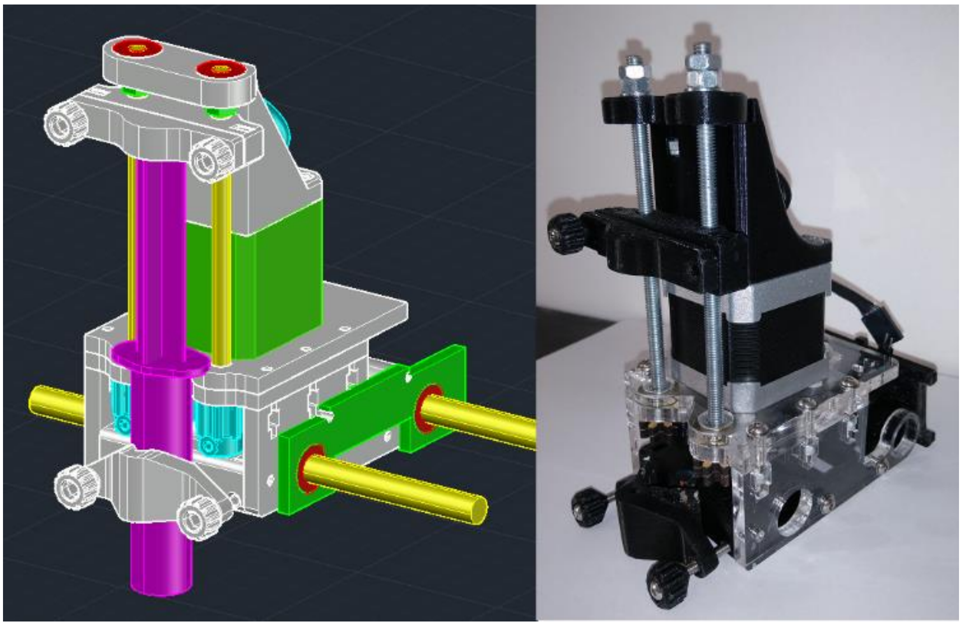


Figure 6 - Design part on the left and printed and assembled on the right.

This adaptor was tested, but unfortunately it was not ideal as the gears did not lock each other perfectly, which meant that there wasn't a constant movement of the plunger. A "Techcon Multi-Purpose Dispensing Valve Controller - TS500R" (figure 7 - a) and a "Techcon Interchangeable Material Path (IMP) Rotary Valve - TS7000" (figure 7 - b) were used to print the material. With this valve, we can control the flow of the material exiting the needle while making sure it has a constant flow.

To adapt the new dispensing system, a new support had to be designed that could hold the rotary valve in the printer's head. In terms of the dispensing controller, this was placed on the bottom of the printer near the main board since there was a limitation on the length of the air tubes that connected the controller to the valve. The Techcon TS500R controller can be used with different types of valves, so not only the rotary but also the "Precision Spray Valve - TS5540" (figure 7 - c) that could make the system work as a low temperature Spray.

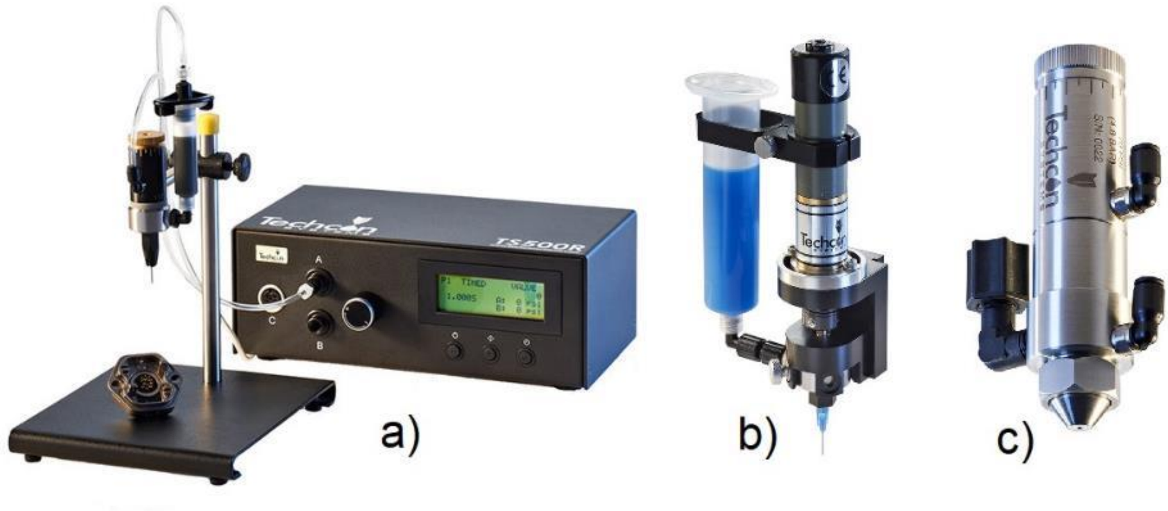


Figure 7 – a) Techcon Multi-Purpose Dispensing Valve Controller -TS500R [14]; b) Techcon Interchangeable Material Path (IMP) Rotary Valve - TS7000 [15]; c) Precision Spray Valve - TS5540. [16].

The laser system to process the materials is a “JTech Photonics 3.8W Laser” (figure 8) which is a Blue laser (between 435 and 455 nm wavelength). With this laser, it is possible to perform the post processing while printing the solution (between layers) in the case of the extruded pastes as well as giving the ability to anneal/sinter films of sprayed solution.

Figure 8 – Jtech Photonics 3.8W Laser head. [17]

To avoid hazards in skin/eyes, the laser light needs to be blocked to the outside of the printer. Previous tests of transmittance led to the selection of an appropriated acrylic, so that it would protect the users from the laser while the inside remains visible. So, after knowing the wavelength from the laser, an acrylic that would absorb that radiation was chosen. It was designed so that the walls of the printer would be extended to make sure the printer could house the new extruder, and there would be easy access inside, so the top panel of the printer opens by lifting from the front and the front doors can be opened by rotating 270º around the structure (figure 9).

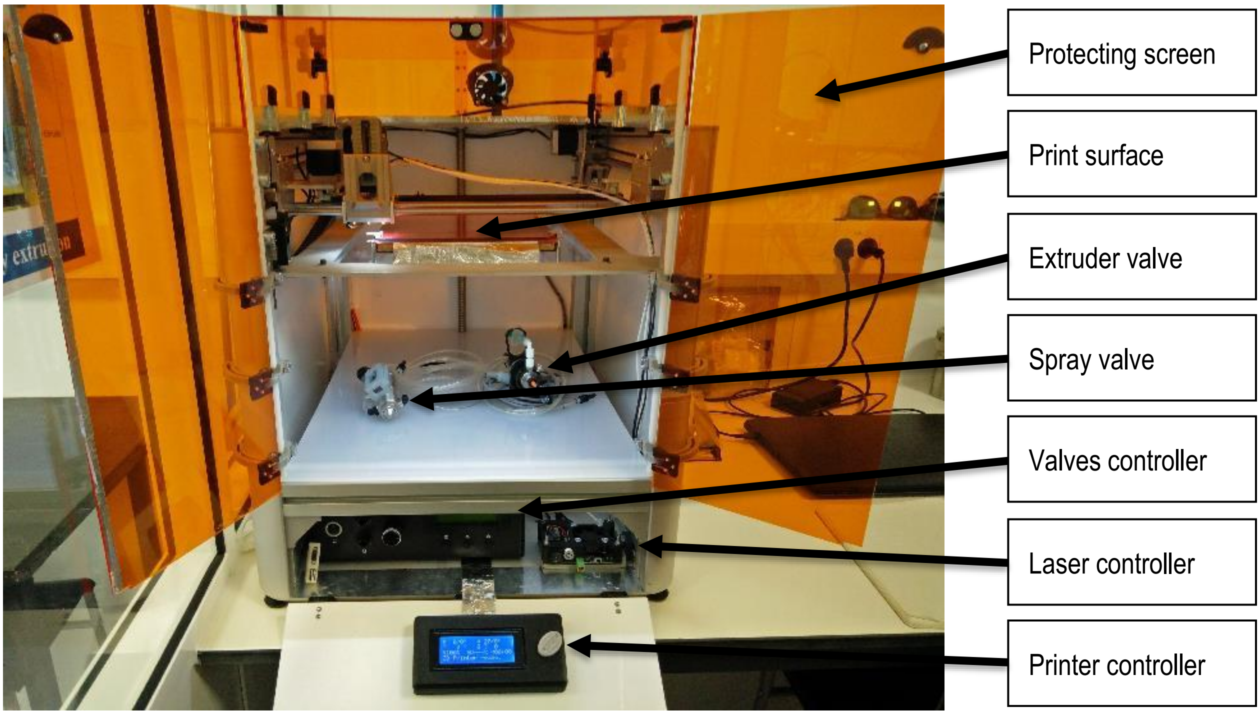


Figure 9 – 3D Printing System.

3. Results and discussion

The main objective of this thesis was to fabricate a functional 3D printing multitask system and this chapter shows the different functionalities. So, there was not a specific study on a certain material or system parameter which means that the results may vary if any of these changes.

3.1. Rotary Valve

The functionality test of the Rotary Valve consisted on setting some parameters that according to previous experience would be more reasonable (table 1) having into account the number of variables in the system. Other parameters can be considered for further printing improvement but for testing the system the ones shown in table 1 were considered suitable.

Table 1 – Parameters and values set for the Rotary Valve tests

Rotary Valve Variables	Values	Units
First Layer Height	0.1; 0.2; 0.3; 0.4	mm
Rotation Speed	2.5; 5.0; 7.5; 10.0	V
Print Speed	5; 10; 15; 20; 30	mm/s
Density	25; 50; 100	%
Layer Height	0.1; 0.2; 0.3; 0.4	mm
Double Wall Support	Circle; Rectangle	--
Inclination Angle	70; 80	º (angle)
Nozzle Size on software	0.4; 0.6; 0.8; 1.0; 1.2	mm

3.1.1. First Layer Height, Rotation Speed and Print Speed

The first tests aimed to evaluate the influence of printer parameters on the first layer uniformity and definition. The photograph of the different tests performed is showed in the table 2 with the indication of the printed path for each condition.

Table 2 – First Layer Height, Rotation Speed and Print Speed tests representation.

Rotation Speed [V]	Print Speed [mm/s]	First Layer Height [mm]: 0.1 / 0.2 / 0.3 / 0.4
2.5	5	
	10	
5.0	5	
	10	
	15	
7.5	10	
	15	
	20	
10.0	15	
	20	
	30	

Table 3 – Line width of First Layer Height for the tested Rotation Speed and Print Speed tests.

Rotation Speed [V]	Print Speed [mm/s]	First layer height [mm]			
		0.1	0.2	0.3	0.4
2.5	5	0.882	0.234	0.354	0.328
	10	0.772	0.398	0.332	0.366
5.0	5	0.811	1.186	1.152	1.178
	10	0.891	0.975	0.760	0.858
	15	0.884	1.099	0.994	1.062
7.5	10	0.859	1.079	1.258	1.329
	15	0.918	0.988	1.420	1.387
	20	0.967	0.881	1.379	1.150
10.0	15	1.055	1.012	1.450	1.114
	20	1.011	0.996	1.208	1.195
	30	0.990	1.105	1.273	--

The First Layer Height (FLH), Rotation Speed (RS) and Print Speed (PS) where tested together, as shown in table 2. This test consisted on printing a one-line perimeter of a rectangle (photograph on table 2) to observe the influence of changed parameters on the width of the lines printed.

By visual observation, we conclude that the 0.1 mm FLH is too small for material exiting the needle properly considering the gap between the needle and the surface, so in any of the cases a non-uniform line was observed. Also, in almost every rectangle there is a little line to the side or upwards, which is caused by the software that generates the GCode, it finishes the print but doesn't turn off the extruder instantly. Some conditions printed lines so thin in terms of height that the material would dry in just a few minutes (the thinner the faster) which led to some of the rectangles to crumble and came off, so in some cases there's only the mark of where the lines were.

According to the to photograph on the table 2 the 2.5 V of RS is to slow to print at the PS imputed, the results were just a few lines and dots instead of a continuous line. Only for the 0.1 mm FLH a full rectangle was printed, but then the height was too small to apply the material properly. On the other hand, for a higher RS, 10 V, it had to move a lot quicker to deposit the material properly, the tests performed show that a lot of material exited the needle and spread to the sides wish led to oversized lines.

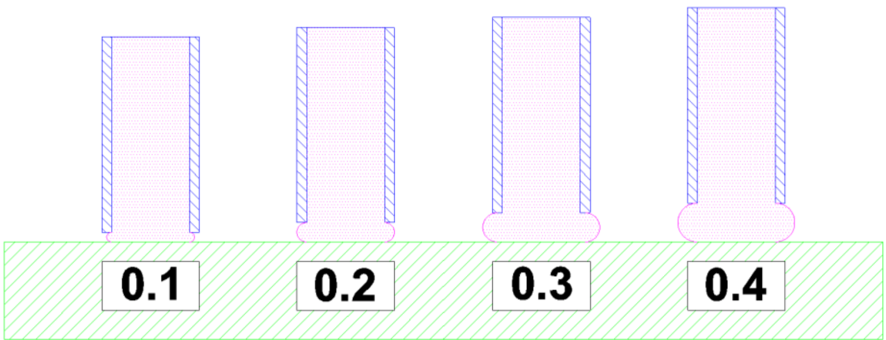


Figure 10 - Representation of the needle distance to the surface (First Layer Height).

The figure 10 is a representation of the gap between the needle and the surface where the material is being applied, it serves to give an idea of what might be happening to the material as its exiting the needle.

Table 3 shows the results of the rectangle lines width. The Inverted Microscope Leica DMi8 with the 50x lenses was used to measure these lines, using its software, it was possible to measure both lines of each rectangle and to get an average. The results confirm the first visual inspection, the 2.5 V rotation speed was too low to be able to apply a good first layer. In terms of FLH, the 0.1 mm is very close to the 0.8 mm (the same as the needle exit diameter) which may indicate that it is too close to the surface, so the material is unable to exit from syringe needle. The 0.2 mm is around 1 mm width and usually for slower print speeds it measures wider then for faster speeds, as it is expected.

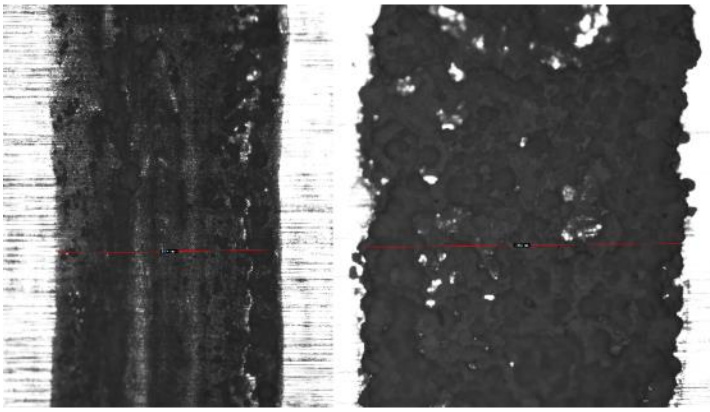


Figure 11 - Side by side figure of 0.2 mm and 0.3 mm FLH.

The microscope observation of the lines makes clear the difference on the width of the lines corresponding to 0.2 and 0.3 FLH, as figure 11 shows, basically on the 0.2 mm FLH the needle would be high enough to let the material out, but not enough so the material would be dragged and in this case, leaving a vale in the middle of the applied material resulting in the spread of the line further to the sides making it wider. For the 0.3 mm and 0.4 mm this was not verified and both values of width are similar, this means that the material is already exiting the needle without being dragged.

3.1.2. Density

A cylinder 20 mm of diameter was printed to evaluate the control on the densification of a printed object using the printing conditions: print speed of 10 mm/s; layer height of 0.3 mm; rotation speed of 6.2 V; and syringe pressure of 2.0 bar.

Figure 12 - Density of 25%, 50% and 100%, from left to right.

Figure 12 shows the photographs of the obtained objects where is clearly seen the influence of densification on the compactness of the pieces. The 25% cylinder, seems to be collapsing into himself due to the gaps left by the lack of density as a result of the viscosity of the material used. The 50% cylinder appear more compact but there's still some gaps between parallel lines. The 100% density cylinder seems completely compact without collapsing, but in opposition the final lines dragged some material and left marks that indicates the need of a bigger layer or a decrease in the maximum density used.

3.1.3. Layer Height

The influence of layer height was tested in the same piece geometry as referred before and in a hollow cylinder in which it can be crucial to keep the walls of the cylinder in the correct geometry without them collapsing.

3.1.3.1. Full cylinder

The layer height tests were performed using a density of 25%. The photographs of the printed pieces are shown in the figure 13 and led to conclude that the parameters varied are only adequate for a small interval of density, and a visual observation led to the conclusion that the ideal value would be 0.25 mm of layer height for 25% density.

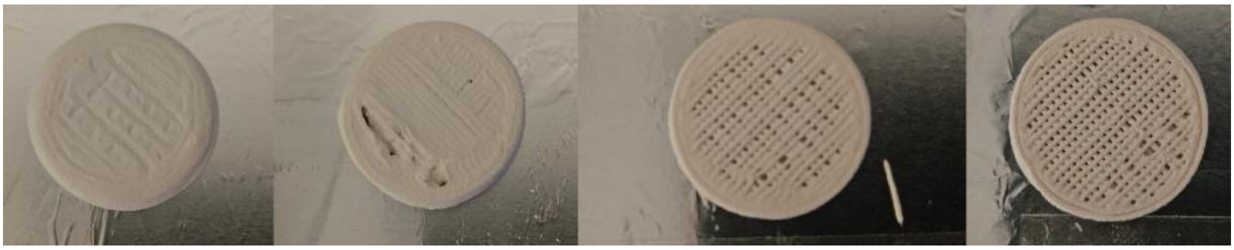


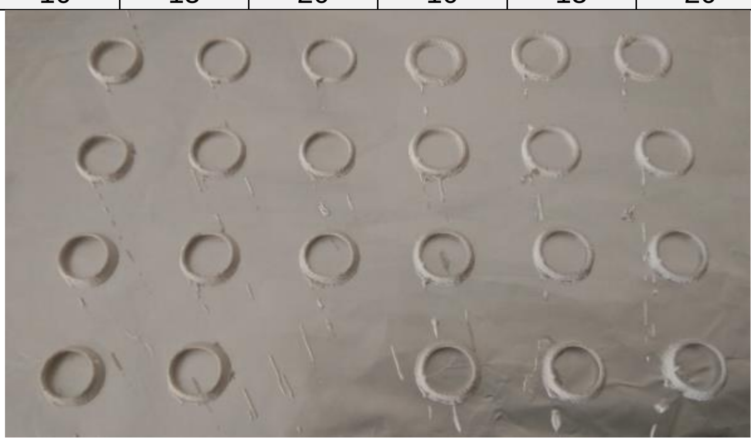
Figure 13 - Layer Height 0.1; 0.2; 0.3 and 0.4, from left to right.

In fact, the 0.1 mm layer height is to small and the material gets dragged around and it is clearly oversized wish led to a deformed shape. On the 0.2 mm it went better than before but still looks a bit imperfect, and unfortunately, right on the end of the print, the material ran out and the compressed air started to come out resulting in the hole. On the 0.3 and 0.4 mm the cylinders look better and perfectly round, but increased height results in non-uniform layers of material since the material gets dropped and does not spread evenly.

3.1.3.2. Cylinder Wall

The influence of parameters on the consistency of a hallow cylinder were tested and the obtained results are shown in photograph present on table 4. The definition of a good wall will depend on the materials, but from material to material there is a need to adjust the parameters to find the most suitable resulting in a perfect object. The round object had also the finality to verify if the combination of extruder/printer has any problem with continuous circular motion and continuous feeding of material.

Table 4 – Layer Height tests disposition, single continuous line.

RS [V]		5			7.5		
PS [mm/s]		10	15	20	10	15	20
LH [mm]	0.2						
	0.3						
	0.4						
	0.5						

The figure 14 shows the prints with greater detail, the 0.1 mm layer height was tried but it just drags the material without really printing a defined line. The 0.5 mm layer was also tried but it was the worst in terms of collapsing. The 5 V of RS and 20 mm/s of PS were not printed due to the fact that the 15 mm/s was already getting a lot of dispensing flaws since it was moving faster than it could print.

Figure 14 - Layer Height tests, single continuous line in detail.

Figure 15 - Layer Height tests, single continuous line, side view of 0.5, 0.4, 0.3 and 0.2 mm.

The side views of each layer height are shown in figure 15. Clearly the 0.5 mm is the one that collapsed the most, also, the 0.2 mm seems to have collapsed, as well as it did drag some material. The 0.3 and 0.4 mm of layer height worked better being the 0.3 the more defined and uniform.

3.1.4. Double Wall Support

To improve the vertical wall while printing, a double wall print was tested and the photographs, figure 16 shows the resulting pieces. For both the circle and the square shape the form stands a lot better with only a small angle defect. Used a RS of 5 V, for PS of 10 mm/s and a LH of 0.3 mm, a smaller cylinder of 10 mm diameter and a 10x10x10 mm cube were designed to which was imposed a double wall print with a continuous line print for both. Comparing one to the other it seems that the cylinder inclines a bit more but when comparing with the results seen before it is much better, also these prints have at least four times the height. Looking at the top view there's a clear place where the extruder rises, indicating that it probably needs to alter the extruding timing so that it stops some milliseconds before it starts a new layer.

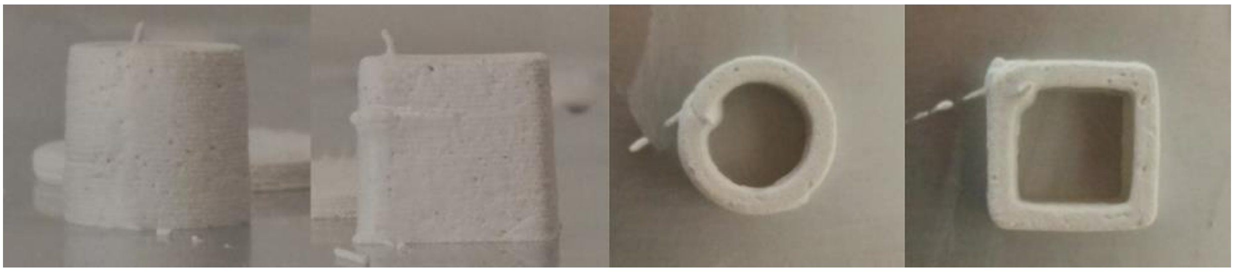


Figure 16 - Double Wall Support, side view and top view.

3.1.5. Inclination Angle

To evaluate the ability of the printer to obtain more complex objects, a test was performed for printing with a certain angle, 80º and 70º to the surface (figure 17). The results may vary depending on the material used, but for this material it worked, even after a couple of days without any post-processing. According to what it was measured (table 5) in ImageJ, the 80º ended up with 76.74º and the 70º had 68.89º which is good although not perfect. Both pieces have 10 mm height and the parameters are the same used before, RS 5 V, PS 10 mm/s and LH 0.3 mm, this means it had 34 layers. Curiously on this print test, the density used had a side effect, by looking at the result it is visible a little deviation of the vertical wall on the left side of the print. This probably was due to the low density (25%), on the full layers the print stayed straight while in the low density layers the print shifted in the direction of the angled wall.

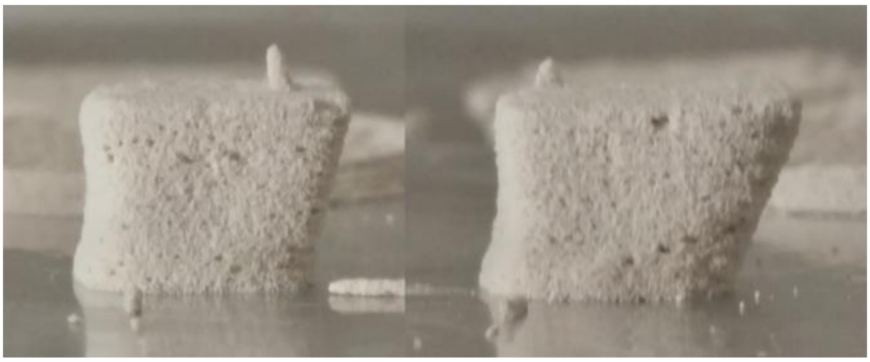


Figure 17 - Inclination Angle tests, side view, 80º and 70º.

Table 5 – Inclination Angle results obtained with ImageJ.

	Incline		Deviation	
Angles	80º	70º	80º	70º
Measure from ImageJ	283.11	291.43	267.79	263.87
	283.34	290.87	267.43	263.88
	283.34	291.04	267.52	263.94
Average	283.26	291.11	267.58	263.90
Standard Deviation	0.11	0.23	0.15	0.03
Value (360º - Average)	76.74	68.89	2.42	6.10

3.1.6. Nozzle Size on Software

The nozzle size input on the software (Cura) will impact the printed object, but it is correlated also with all the parameters seen before. So, for instance, if we select a bigger nozzle size on software but at the same time increase the rotation speed it will maintain the ratio. In this test, we have maintained the parameters used before, RS 5 V, PS 10 mm/s and LH at 0.3 mm, and tested the different nozzle sizes, started with 0.4 mm on the left, then 0.6 mm, 0.8 mm, 1.0 mm and last on the far right the 1.2 mm (see photographs of the prints in figure 18). The gaps along the lines were probably due to the air bubbles in the material within the syringe.

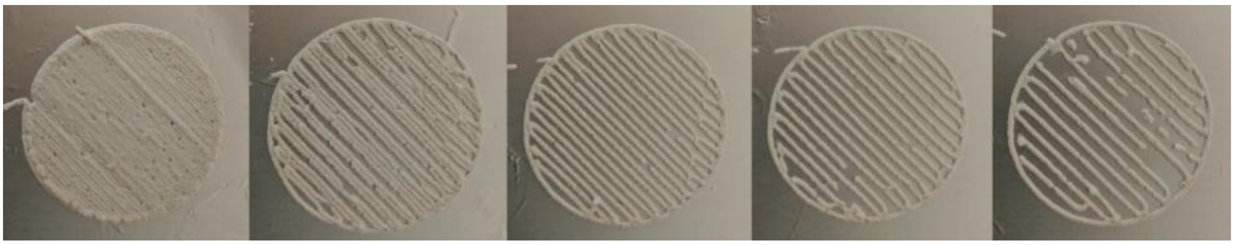


Figure 18 – Nozzle size on software one layer only tests, 0.4, 0.6, 0.8, 1.0 and 1.2 mm.

The layer with the 0.4 mm nozzle size looks completely closed, which is good but at the same time it is too close. There are some failures on this first sample, a line that seems higher than all the rest suggesting that is on top of others, and the border, caused by the way the software gives instructions, first the outer wall is printed and then it goes for the 45º lines, so the border between both seems to be above the rest. The 0.6 mm looks acceptable, although the lock-like a flat surface print is due to the height of the needle, it looks as the material was dropped and in some cases, it glued to the line printed before. Also, from another point a view, in some areas the lines are really close which might be an indication that if the height were smaller it would overlap the lines too much. At 0.8 mm the print looks good, it looks like a continuous obliquus line with the right amount of overlapping with the outside wall. This might be related to the fact that the needle exit diameter is 0.8 mm and the height between needle and substrate. For the 1.0 mm and 1.2 mm nozzle size the lines seem too far apart and even the edges of the obliquus lines barely touch the circle which suggests that it was too wide to print properly.

Figure 19 - Nozzle size on software five layers test, 0.4, 0.6, 0.8, 1.0 and 1.2 mm, from left to right.

A five-layer test was also performed with the same conditions, as the first layer might not be the proper height but the ones that follow should be. The photograph of the samples printed presented on the figure 19 confirmed that, the 0.6 mm looks the best.

The 0.4 mm sample was again to close which led to an overlapping of material noticeable on the obliquus lines and on the circle. For the parameters used, the 0.6 mm seems to be the more uniform and without many defect or overlapping, it is completely closed without looking like the print is deformed and the lines were touching the circle and closing perfectly. For the others, 0.8 mm, 1.0 mm and 1.2 mm the lines are all spaced apart showing the grid from the shift in the angle of the obliquus lines between each layer.

3.2. Laser

The JTech Photonics 3.8W Laser is a simple system that needs only to be attached to the equipment and can be adapted to any situation, which in this case the idea is to be used as a post-processing part of the system. For now, the tests performed (seen in table 6) aimed to verify its functionality. The first test was a manual focus, rotating the lenses until the smallest spot possible. The second was a variation of power, to understand the range of power expected.

Table 6 - Parameters and values set for the Laser tests.

Laser Variables	Values	Units
Focus	Manual	--
Power	10 to 100	%

3.2.1. Manual Focus

A small screw and cap with the lenses inside are rotatable clockwise or counter-clockwise, wish changes the focus according to the height to the material (left side of figure 20). The ideal focus height is around 75 mm, which was advised by the company on the instruction manual. The system has a double switch to turn the laser ON (a simple ON/OFF switch) and a safety key switch. Also, it would only be ON if the printer electronics send the command to do so.

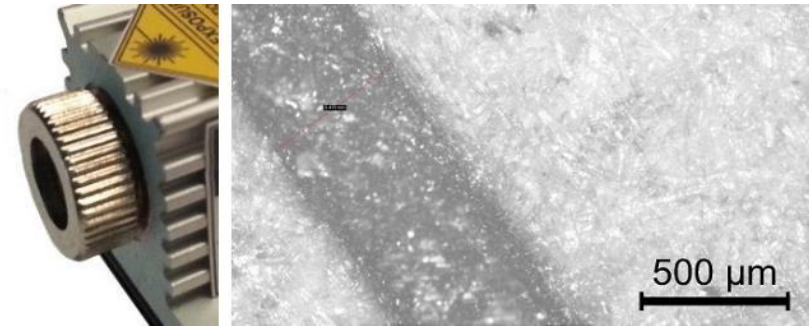
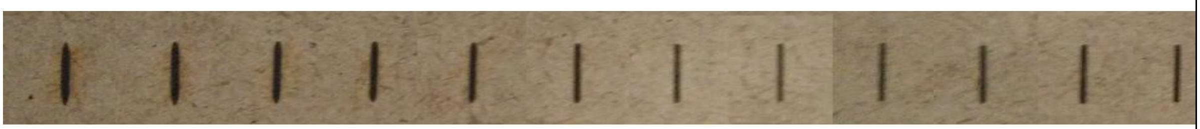


Figure 20 – JTech Photonics 3.8W Laser, emphasize on the lenses Manual Focus tests on the left and on the right, is measurement on Leica Application Suite Software of the width of the line produced by the laser.

To perform this test a small MDF board was used and a small 10 mm line was drawn, then the board was just moved forward by hand between each test performed. The procedure was turn laser ON, start print, burn the line, turn laser OFF on both switch and safety key, move board, turn laser ON again, etc.

Table 7 – Width of the lines produced by the 12 rotations and laser scribing on MDF with different focus.

0.783	0.652	0.688	0.624	0.577	0.519	0.531	0.494	0.490	0.484	0.479	0.469
											

The table 7 contains the lines obtained by the 12 rotations performed on the lenses. Considering that the correct height (or thinnest line) was achieved around the tenth rotation, the next adjustment was in the same direction but the last one was in the reverse direction to get to the right focus again. As a bonus with the last rotation, the focus got even better resulting in the thinner line.

All the lines were measured on the Microscope Leica DMi8 with the 50x lenses and, as can be seen in the photograph presented on the table 7, there's not a clear edge where the side of the line begins which may lead to some small error on the values obtained (table 7). The smallest value obtained was 0.469 mm on the final adjustment. According to the lasers company the minimum size of the laser spot is approximately 0.36 mm, but since the paste extruder usually leaves a line greater than that, there's no need for now to try to get the laser spot even smaller.

3.2.2. Power test

The power's influence was observed by varying the percentage of power of the laser and observing the depth and width of lines (see figure 21). To perform this test a scale with increments of 10% in power was made in a single file. But, since the laser firmware reads values from 1 to 255, in order to control the laser, the percentage would have to be adjusted to these values, so the table 8 show the values needed. The produced GCode file had 10 lines with 10 mm long and some space between them.

Table 8 – Power scale used on test.

Percentage [%]	Value used
10	26
20	51
30	77
40	102
50	128
60	153
70	179
80	204
90	230
100	255

Figure 21 - Power test.

3.3. Spray Valve

The inclusion of a spray valve in this 3D printing system was to enhance further its functionalities. Therefore, the spray valve needed to be tested as well. So, variables such as time, pressure and exit width were tested. Table 9 shows the values of parameters varied and since the speed, distance and temperature were independent from the valve they wouldn't be in these tests.

Table 9 – Parameters and values set for the Spray Valve tests.

Spray Valve Variables	Values	Units
Pressure	0.5; 1.0; 1.5	bar
Dispersion Time	0.2; 0.4; 0.6; 0.8; 1.0	sec
Dispersor Exit Width	Manual	--
Dispersion Height	10; 20; 30	mm

Figure 22 - First spray of water onto a glass substrate with the Spray Valve.

The solution used was just water so it's not easy to see the result, also the glass is not the ideal surface to analyse the spray result. To solve this, a solution with some colouring was used and it was sprayed on a simple A5 sheet of paper.

3.3.1. Pressure vs Time

The photograph on the table 11 shows the results of the test performed, it was used a spraying time of 0.2, 0.4, 0.6, 0.8 and 1.0 seconds and a pressure of 0.5, 1.0 and 1.5 bar.

Table 10 – Area [mm2] results for spray test, Time vs Pressure.

		Time [s]				
		0.2	0.4	0.6	0.8	1.0
Pressure [bar]	1.5	365.8	429.9	549.6	533.4	574.3
	1.0	193.1	348.5	398.8	402.1	420.1
	0.5	110.4	152.0	178.9	185.6	208.7

Table 11 – Area [mm2] results for spray test, Time vs Pressure.

		Time [s]				
		0.2	0.4	0.6	0.8	1.0
Pressure [bar]	1.5					
	1.0					
	0.5					

The table 10 shows the area measured for the spot of solution on the paper sheet caused by the spray. The 0.5 bar tests seem to be just a drop since there was not enough pressure to push the solution outward and therefore has the smallest areas. The 1.0 and 1.5 bar tests are far better, and it is visible the difference between the two where the higher pressure makes the mark larger. One particularity of the high pressure is the spread coming from the centre of the mark, the longer the time it spends spraying, the wider is that spread.

3.3.2. Exit Width

The spray valve has a manual regulator to control the solution caudal width. For this test it has been chosen 3 consecutive marks seen inside the blue rectangle on the figure 24. The time vs pressure test performed before corresponds to the red mark aligned with the left mark of the blue rectangle, the middle mark corresponds to the seen next and for the line on the right of the blue rectangle, the amount of solution exiting was too much so it wasn't considered. Also, to the left of the first line in the rectangle there was no solution exiting so there's no test for it.

Table 12 – Spray test, Exit Width area [mm2] results.

		Time [s]				
		0.2	0.4	0.6	0.8	1.0
Pressure [bar]	1.5	926.5	1365.2	1361.4	1379.2	1512.5
	1.0	649.6	863.7	939.0	1082.2	1058.2
	0.5	222.5	302.9	398.5	446.8	594.6

Table 13 – Spray test, with different exit widths.

Figure 23 - Manual control of the valve.

		Time [s]				
		0.2	0.4	0.6	0.8	1.0
Pressure [bar]	1.5					
	1.0					
	0.5					

The results (table 12) obtained on the test shows a similar result to the test presented before but it leaves wider marks on the sheet of paper. The longer it's spraying, the wider the marks are and the higher the pressure is the wider the marks will be. Another consequence of longer times is the larger the "tentacles" as can be seen in the photograph of the table 13. Also, a detail seen in this test is that for the 0.2 and 0.4 seconds of 1.5 bar, it seems that it left a blank centre of the solution mark, probably due to the small interval of time it was spraying it didn't had enough time to fill the hole.

3.3.3. Height

On this test, the time parameter was the same as before (0.2, 0.4, 0.6, 0.8 and 1.0 s), the pressure parameter was maintained at 1.0 bar and the test performed (table 15) was the height of the nozzle to the surface. In this case the height used was 10, 20 and 30 mm.

Table 14 – Area [mm2] results of the spray test, Height.

		Time [s]				
		0.2	0.4	0.6	0.8	1.0
Height [mm]	30.0	433.8	535.9	731.0	814.6	914.4
	20.0	423.1	622.1	669.8	697.5	768.1
	10.0	399.5	483.8	517.5	524.8	690.4

Table 15 – Area [mm2] results of the spray test, Height.

		Time [s]				
		0.2	0.4	0.6	0.8	1.0
Pressure [bar]	1.5					
	1.0					
	0.5					

On the table 14 the results of the area measured show the higher the nozzle gets, the wider the mark of the solution. One particularity of this test is that the height makes a difference on the deposition of the solution. The “tentacles” seen on the test before are now only present on the 10 mm height tests, so it may suggest that the “tentacles” are a consequence of solution the is being dragged away from the centre of the spray. Another visual characteristic of this spray test is the uniformity of the marks. The solution seems to be sprayed more evenly since it has the space to travel from the nozzle to the surface.

4. Conclusions and future perspectives

This thesis main objective was to fabricate a 3D printing system that would be able to print with different materials and/or different viscosities and had a post-processing technique integrated. In addition, some tests were performed to understand and make sure the 3D printer worked properly with all the integrated systems.

The Multi Material 3D Printer built consisted first in finding a suitable structure that would support all the systems needed. The “Leapfrog Creatr 3D 2014” had a very sturdy frame and ideal for this system and since there was one located at the lab that wasn’t being used due to its multiple problems it was the perfect candidate to use for the system.

First task performed was taking the Leapfrog apart and understanding its problems, it had issues on the wiring, its board was faulty, and the end stop sensors didn’t always worked. All of it was fixed or replaced in the case of the main board and the power supply, also, a LCD with a SD Card reader was added to make the system independent. Then to test the ability to print viscous materials, an extruding valve was design and printed to perform this task which was then attached to the printer and tested. A better alternative was then found, an independent system that could be used for extruding or spraying. An adapter was again design and printed that would hold the independent system heads. Lastly. on the built, a laser module head was attached to the adapter printed before and the controller stayed on the bottom of the printer. Some acrylic screen was added to prevent the laser radiation from being hazardous to any user.

The next step were the tests to confirm that the printer worked accordingly by starting with the extruder and its First Layer Height, Rotation Speed and Print Speed. The tests showed that the 0.1 mm height is too small to print, the 0.2 is higher but still not enough to leave a good base, the 0.3 mm was the ideal according to the parameters used and the 0.4 mm might be a good height but there should be an adjustment on the speeds to compensate the heights.

In terms of the Density test the main characteristic that did contributed for a good or bad print was the viscosity of the material, that had a significant impact on the final print quality. On the Layer Height the conclusion is that for the parameters used the 0.2 and 0.5 mm were not good, the best were the 0.3 and 0.4 mm and from both ideally the 0.3 mm would be the layer height used these parameters.

As for the Double Wall Support, it has proven that by adding a second wall the print gets a lot stronger in vertical terms. In the Inclination Angle, it showed that the print can support an angle of 70º or 80º to the surface, only if is the density is above the 25% or it may drag the material to the side. The Nozzle Size on Software must be as close to the needle size as possible. In accordance with the tests performed on the one-layer print, the best sizes were the 0.6 and 0.8 mm, but it has a lot to do with the height of the needle in relation with the surface. As for the 5 layers print the best height was the 0.6 mm.

The Laser tests consisted in the manual focus and the power control. Both were successful as the manual was just a matter of rotating the lenses manually to get the minimal spot possible that turned out to be 0.469 mm. The power test was just controlling the output of the laser and see the effect it performed.

To conclude the tests, it came to the Spray Valve, were the parameters tests were the Pressure, Dispersion Time, Disperser Exit Width and Dispersion Height. Started with the first two, the 0.5 bar wasn't enough to produce a spray, but the 1.0 and 1.5 bar were good. The only detail were the "tentacles", the height wasn't enough for the solution to be sprayed so it was "pushed". The longer the dispersion, the wider the "tentacles" were. On the Exit Width, the test was with a larger exit and the conclusion is that performed in a general way as the pressure vs time test, only that it was wider. The height had an expected result. As before the height was small, now for 10, 20 or 30 mm height the spray mark left was wider and more even.

For the future, each material used should be tested for all the parameters seen in this thesis, it will always have a different result than seen here. Also, the laser can be used for material processing and not exclusively for post-processing.

If this system proves to be useful, a new one should be built. Now knowing what is needed and what it can do, a better system can be fabricated. Maybe try to isolate the atmosphere and make it more bio-compatible.

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