3D printing system for ceramic materials: design and testing of an experimental rig

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Abstract

In the context of a constantly growing additive manufacturing market, many processes are acquiring important statuses in the medical field. Particularly for dental restorations where those manufacturing techniques helped to produce more performant implants to solve both plastic and functional problems of deteriorated teeth. As restorative materials, ceramics became increasingly popular because of their aesthetics, inertness, mechanical properties and biocompatibility. Thanks to its inherent ability for complex geometries fabrication, additive manufacturing has thus gained significant interest to realise quickly available customized pieces with low material consumption, which led to lowering the costs of the most popular dentures. However, some uncommon prosthetics still remain impossible to produce or are overpriced. The motivation of this study is to help filling this gap by adapting the economic advantages of the FDM process into a solution for the dental medical care.

To do so, the aim is to create an experimental rig for ceramic paste deposition, which purpose is to allow the testing of several parameters to assess the printability of the material. This prototype is done by designing a hardware adaptation of a 3D printer, originally operating with the method of fused deposition modelling, to make it capable of liquid deposition modelling process. A preliminary literature survey on rapid prototyping with 3D printing was led, with methodical tests on key factors of printed parts quality, in order to adopt an effective development strategy based on CAD.

A functional prototype was manufactured with positive overall results in terms of functions and geometric freedom for production. A maximum amount of original hardware and 3D printed parts were used to ensure an affordable reparability and modularity. Finally, this experimental rig is considered as a first iteration that can be improved and adapted to specific manufacturing needs in the future.

Key words: Design for manufacturing, additive manufacturing, liquid deposition modelling, zirconia pastes, manufacturing strategy, experimental prototype.

1. Introduction

The recent introduction of Additive Manufacturing techniques in the medical field has marked a turning point in the prosthesis production technology, from the traditional hand made to the innovative automated approach. Particularly for the dental market, this manufacturing method offers advantages of being faster, more efficient and leads to less waste material compared to conventional machining. The speed and ease-of-use of those technologies open the possibility for dentists to design and produce custom dental crowns directly in their offices. Additive manufacturing known a breakthrough in the dental machining market, which gained a growth of 35% in number of sales between 2016 and 2017. Regarding the opportunities provided by additive manufacturing, new restorative materials have been lately developed and massively adopted. That is especially the case of dental ceramics, which presents outstanding biocompatibility properties along with excellent ratios between mechanical and aesthetics functions. However, the production of all-ceramic crowns and bridges is still quite incipient, whose mainstream adoption is estimated to take place in at least 5 years (Peng et al. 2018). One of the main reasons is that additive manufacturing developments are mainly focused on metal alloys and polymers, when slower progress leave the ceramic fabrication market ruled by still overpriced high-end printers. This work thus intends to contribute developing this market, as well as to help affordable medical solutions progress in the long run.

The aim of this work is the result of a common willpower of the Lab2Prod of the Mechanical Engineering Department and the BioMat Research Group of the Chemical Engineering Department of Instituto Superior Técnico Lisboa. The objective is to develop an additive manufacturing experimental rig for liquid deposition in the Lab2Prod, whose purpose is to work with a printable ceramic paste prepared by the BioMat Research Group. The overall product should allow the mastering of a maximum of additive manufacturing related parameters, in order to test the printability of the paste and determine a related range of correct production settings.

A functional prototype will be built from an existing 3D printer frame working with Fused Deposition Modelling. The tool head of the machine will be replaced on the actuated carriage by a Liquid Deposition Modelling-capable extruder, which needs to fit the original extruder precisions and bulkiness. Since the experimental rig's mission is to test small-scaled samples of ceramics, the new extruder's operation will be based on standard syringe and short reservoir, chosen among those already in use in the BioMat Research Group. This adaptation will be done by reusing a maximum of the original components and realised largely thanks to parts that will be 3D printed in the Lab2Prod, to ensure modularity, ease of adaptation and maintenance of the prototype.

2. Theoretical Background

Since the arrival of computers in the manufacture world a few decades ago, traditional machining has been highly improved, and a plethora of new production processes has been developed in the manner of AM tools. Nowadays a same object can be produced in many ways, each method with evolving drawback and advantages regarding the others, allowing manufacturers to constantly improve production times, energy consumptions and material wastes.

2.1 Additive manufacturing

Quite recently introduced to the large public, Additive Manufacturing is a method of manufacture where layers of a material are build up one after another to create a three-dimensional object. It is an inevitably computer-assisted technology whose actions are originated on a digital 3D model of the object to be manufactured. Through machines based on various technologies, materials such as plastics, metals and even ceramics can be processes through this layer-by-layer method. This unique method allows the creation objects of almost any shape and geometry with virtually no upfront machining nor production lead development. However, it is a low cost but typically slow and non-scalable method, meaning that increasing number of units for production does not decrease price per unit. Thus, AM use is restricted to rapid prototyping, single units or small batch production. On top of that, the mechanical properties of produced parts depend on lot of parameters and are still hard to predict because of lack of knowledge about it.

The strengths of AM lie in those areas where conventional manufacturing reaches its limitations. The technology gains its full interest by enabling a way of production where the design determines the manufacturing, and not the other way around. All through its enhancement, AM acquired more and more accuracy and is working with an always wider material range. Especially when combined with other process AM is very likely to enter numerous types industries during the following years. What is more, AM allows overly complex structures that can still be extremely light and stable, which is a particularly important characteristic for medical bio engineering. It provides design freedom, optimisation and integration of functional features as well as manufacture of small quantities at a high degree of customisation for a reasonable unit cost.

2.2 FDM process

By combining both previously explained AM benefits and low-cost easy to use materials, the Fused Deposition Modelling process allows highly customable fast prototyping. Those characteristics are a solid match for the needs of this project to develop, test and confirm solutions in a short span of time as well as for building main parts of a functional prototype. All of that with reduced costs and easy to repair parts by re-printing them on site. As for every AM process, the first step of FDM produced parts always starts by the design. Once the design done, the link between CAD and CAM is made by processing the STL file through a software that will then give orders to the machine. This main CAM software is called a slicer because that is where the STL file will be divided into virtual layers, which with the printer will then work. We can see this step as a virtual environment of the machine were all the printing parameters are decided. Then for physically printing, the material is stocked as a filament usually of 1.75mm or 2.85mm of diameter, on a spool that is free to rotate. A mechanism called the extruder puts the filament in movement thanks to a ribbed pulley attached to a motor and a tensioner. The filament is then directed in to a sheath from the extruder to the hot end. A hot end sets the temperature of the material above its melting point. A cooling system prevents the heat to spread in the filament located in the sheath. The molten material then flows through a nozzle of a specific diameter, to be dropped off on the object to build and quickly cooled down to solid material. Motors allows the printing head, composed of the hot end, the nozzle and the cooling system to move according to the shape of the object to form a layer. Once a layer is finished, the bed or the printing head moves of a layer’s height and the process start again to form another layer.

Due to the very principle of layer manufacturing, some effects that can be observed on every AM process are particularly clear when manufactured with FDM. One obvious but important limitation is the layers orientation when 3D printing a part and lot of complications can occur because of the bad management of this aspect. First on a mechanical point of view, FDM components are inherently weaker in one direction due to the anisotropic nature of layer orientation. Since the layers are printed as a round-ended rectangle, the joints between each layer are actually small valleys where a crack can easily form. Those stress concentrations and the lack of continuous material paths contribute to the object's weakness. Another problem of this process is linked to the machines resolution along different orthogonal directions, which directly depends on the nozzle diameter for the X and Y-axis and on the capable layer height for the Z-axis. The first limitation that comes out of this resolution is the staircase effect. As the Cartesian system of the machine interpolates curvatures into a discretised number of layers, the CAM object cannot exactly follow the CAD file. This effect can be observed in the X and Y directions where it depends on the motors step but is particularly marked in the Z direction because of the minimal reachable layer’s height that is more significant than motors steps

On top of that, in practice, some other issues can appear and those depends on the printing conditions in the machine. The situation in the printer is determined by a plentiful of parameters that are usually controlled by the slicer during printing or through the G code file. A bad calibration or combination of those parameters can cause many printing defaults as seen on figure 2.1.

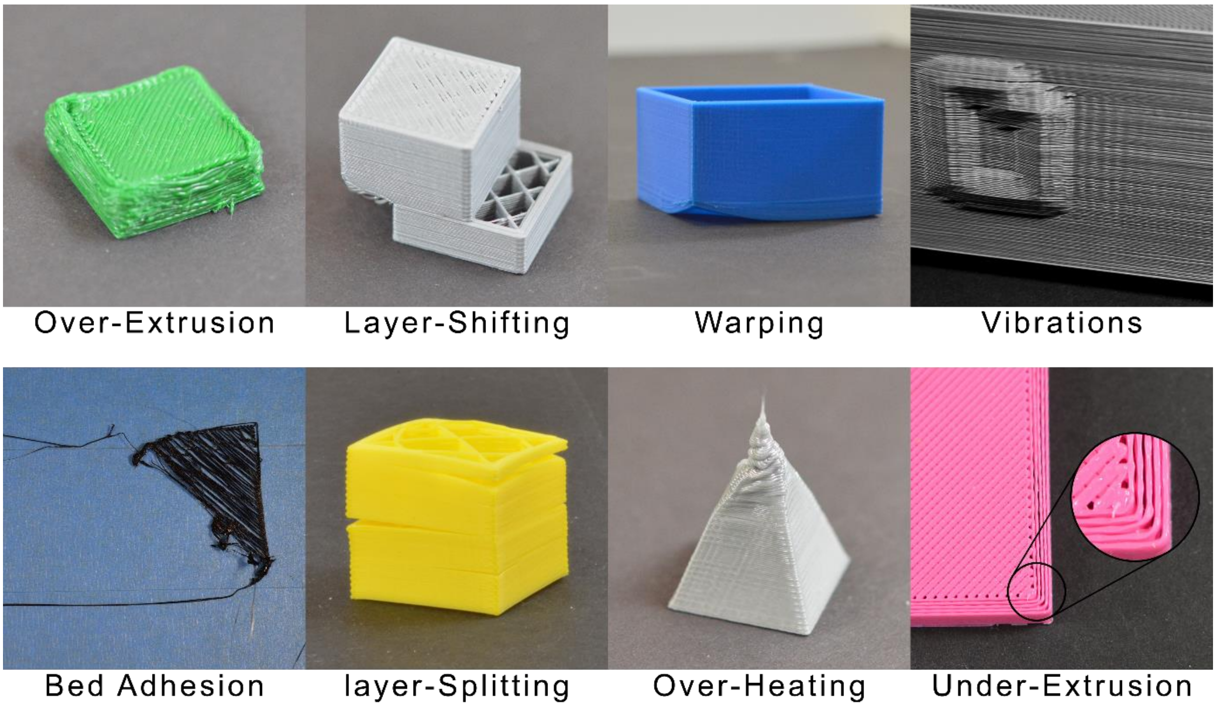

Figure 2.1 : Illustration of common FFF printing problems, adapted from *Simplify3D*

2.3 Zirconia paste for prosthesis

Nowadays, the use of composite ceramics is increasing compare to classic metal alloys, especially for their excellent combination of mechanical and aesthetic properties. They also are highly resistant to acid and corrosion attacks and are therefore regarded as exceptionally biocompatible and chemically durable on a very long term (Sarasota 2017). However, in addition to prohibitive costs and relatively long manufacturing time of ceramics, there are relevant issues related to their potential for brittle fracture and for abrasion of opposing natural teeth or weaker restorations. The development of a 3D printable ceramic paste thus aims to improve conditions on those issues. The developed cement to be printed by Liquid Deposition Modelling (LDM) is actually a suspension of about 90 % weight solids formed by a mixture of ceramic powder, water and additives that act as chemical modifiers.

Properties and composition of the paste are crucial factors to ensure mechanical abilities of prints. During extrusion, the paste should be homogeneous and free of air bubbles, contain a high-volume fraction of ceramic powder, flow properties suitable for extrusion and still be capable of maintaining its shape after printing. Thus, inks should be highly shear thinning to allow extrusion through fine nozzles and retain a degree of stiffness to prevent from collapsing and allow self-supporting during printing.

3. Experimental rig design

The main goal here is to design and build the experimental rig for ceramic paste deposition, by transforming an existing FDM hardware into an LDM capable machine. Intention being to obtain a machine able to work with several ceramics having distinct properties, to study their behaviour and test associated printing parameters to ensure correct deposition of each layer. This will be done by conceiving a paste dispenser operating with a syringe and needles, which is then intended for replacing the tool head on the actuated carrier of a FDM printer. In order to allow physical modifications supposedly compatible with the associated software and without breaking any costly guarantees, the FDM machine will dispose of an open source system. The machine to be built also needs to respect objectives set by the BioMat Research Group who wishes to test materials and operate this system by its own in the future. In addition, of constraints set by adaptations to ensure transition from FDM software to LDM hardware, those requirements mostly concern precision and ease of use of the machine.

The paste extruder of the machine should use syringe and needles that follow medical standards to ensure compatibility with probable supplementary systems and allow stock orders from several suppliers. A choice should be possible among those standardised needles to allow several extrusion diameters. This will be useful to adapt the system to the different rheological natures of future pastes or simply to allow fine and coarse extrusion for both precision prints and time saving prints. The system should provide control over a maximum of printing parameters to obtain decent prints for several inks and under different conditions. The maximum precision the overall system can reach should be able to fulfil the dental market sizes requirements. Design the hardware to make it as easy to manipulate as possible and thus avoid misuse, shocks with glass parts and premature deteriorations. If possible, adapt the FDM software to take in count as much LDM parameters as possible, like the change of needle sizes, and to be simple to use.

3.1 Design Method

Not being only focused on cost effectiveness and simplicity of manufacture, the main idea here was to plan the design phase in a way to respect the short limit of time imposed by the ordering delays. Research of solution for the syringe based liquid extruder were thus divided into subsections aimed at solving one problem at a time, the first one being to get to know the manufacturing equipment. This also allowed limiting FDM print failures by understanding limitations of the printers and materials as well as providing ease of adaptation by redesigning and reprinting only a fraction of affected solutions. Finally, the state of mind while designing was also to think solutions and printable pieces as simple as possible to limit weak parts and hard maintenance work, due to elevated number of components or too complex shapes.

First step before conceiving any solutions is to understand limitations of the tools regarding overall mechanical properties of printed parts, times of print, finishing qualities and be able to estimate the failure chances of a print. Second key point is to design with versions, a version being a practical design of the whole project, embodied by CAD files divided in sub folders, each of them focusing on one of the identified problems. Especially to avoid poor mechanical properties the idea now is to design parts that are as simple as possible. Since we are producing most of the parts with FDM, complex shapes are much easier to obtain than with conventional machining, thus it will more be a small CAD step than a CAM complication. To avoid future problems of compatibility and stocks concerning the basic fastenings present in the conception, it was decided to limit the use of different screw sizes by adopting a uniform dimension for screws, bolts and nuts. This strategy also allows to determine once the corresponding holes dimensions on a test print, then repeat them on CAD files without running tests each time, as well as avoiding maintenance confusions for future co-workers.

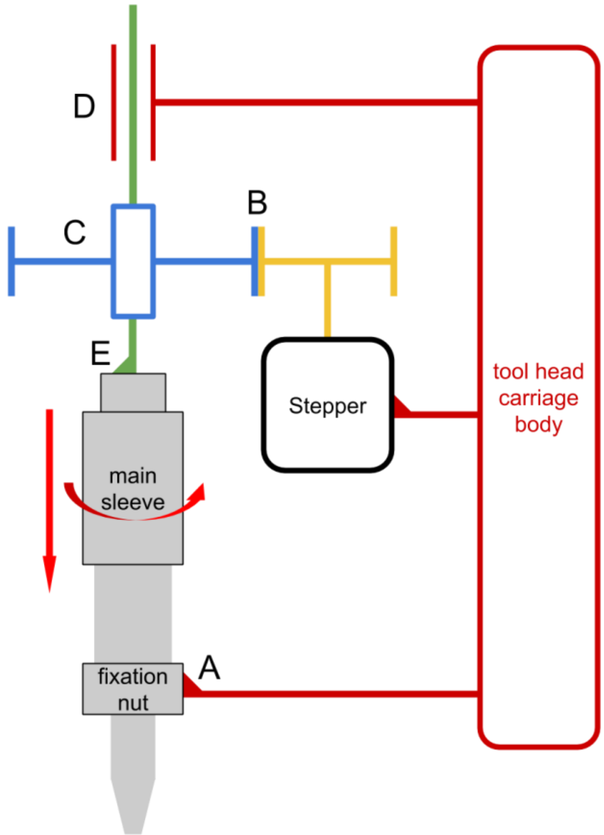

Figure 3.1 : Kinematic diagram for LDM extruder with micrometric syringe

This figure 3.1 displays the first functional solution that was considered for technical design solutions. However, interface **C** was a space demanding solution, problematic for the LDM extruder that needs to be installed in an area limited in height. Meant to transmit rotation while being maintained to carriage body, the **D** connection was also leading to elevated level of complexity for printable parts or elevated price for commercially available solutions. This diagram thus evolved into a simplified adaptation, which suppressed the **D** pivot by integrating it into the blue/green parts connection in **C**.

An important part in the understanding of print fails and overall aspect was to know about printing properties of the main materials to be used during manufacturing step. The table 3.1 below compares values found after calibration and experimentation with the ranges given by suppliers supposed to adapt to most machines. To ensure low print fail rates for this project, raw supplier's data were not precise enough because they rely on many parameters that were fixed in our case.

Table 3.1 : Adjusted printing parameters for a layer height of 0.15 mm on the Ultimaker3

Material	Supplier	Recommended		Adjusted		
		Nozzle (°C)	Speed range (mm.s^{-1})	Nozzle (°C)	Bed (°C)	Max speed (mm.s^{-1})
PLA	RepRap	195 - 215	30 - 90	210	60 - 65	70
	Lulzbot	190 - 210	15 - 70	205	60	60
ABS	Ultimaker	225 - 250	20 - 80	235	85 - 90	50
Nylon	Ultimaker	230 - 260	20 - 60	240	70	50
TPU	Recreus	215 - 250	10 - 70	230	50	15 - 30

After finding the parameters to obtain correct prints, the global observations were concerning the ease of use of those materials to later decide of their adoption for specific parts. Even when extruded under decent conditions, printing with Nylon remains hard to master because of regular issues with layer adhesion and a tendency to warp. Manufacturing phase will favour ABS since it has quite comparable mechanical properties but is easier to print with. TPU printing also depends on humidity and is as hard to use as Nylon, but its rubber like aspect could be nevertheless interesting for joints, pads and potential flexible parts. Since the geometrical differences between CAD and printed parts does vary with the materials, a few dimension tests were also led. For instance, a dimension shift can appear when slicing, due to impossible match between desired length and discretisation that fits layer's height or nozzle diameter

After finding a range of correct printing settings, the goal was to understand the properties of each materials in order to allocate them to the various parts to be produced, in particular those of the body to be designed. Those properties, crossed with the previously tested printing ergonomics for the same materials, allowed to apprehend their sturdiness for different infills and wall thickness values. For instance, it was decided to use TPU exclusively for gaskets or pads to protect the glass parts. After that, ABS was chosen for stiff parts like supports where precision is needed. Those supports will be completed with smaller connections printed in softer PLA to adapt to X carrier geometries.

3.2 Fastenings

Most of the assemblies were designed to use bolt and nuts instead of thermal inserts, imposing a few adaptations. First one is to anticipate the place used by bolt's head and nuts in the global design, which can impeach desired contacts between parts when badly positioned. Then the design must make sure there will be enough space to operate tools to assemble those fastenings along with the other parts of the prototype. If not this problem can be bypassed by integrating a nut-cap in the design, which will block the nut in rotation thus allowing to screw the bolt without having to use two spanners. Finally, there is also a problem due to brittleness that makes those thermoplastics quite sensitive to cracks when fastened with small metallic parts. A few solutions can attenuate this problem, like dividing loads onto several fastening points or use washers to extend contact surfaces on bolt heads. Manufacturing issues can also create misalignment or gaps that could be corrected by combining round and oblong holes in the design. For the same reason of brittleness oblongs will be favoured for ABS parts that are slightly stiffer than PLA

Since there are lot of those fastenings, decision was taken to use a standard size for as many bolts as possible. First argument to choose the bolt size was to pick it among the regularly ordered metric standards used in the Lab2Prod, from M1 to M6, to minimise the out-of-stock and tools compatibility issues. The second criterion was based on practicality to handle standard items and their bulkiness, like bolt heads or flat washers (EngineersEdge 2018). By experimentation, bolts smaller than M2,5 were bothersome to work with and sizes over M4 were judged too bulky for small features requiring nut-caps and potentially dangerous regarding cracks. So far since it is the size already used to fasten the steppers, the best compromise was M3

For the same reasons and to avoid fragile parts the bike inspired clamps were cut down into hinged clamp relying on a long M3 bolt and without rapid fastening arm. Those clamps were applied with adapted dimensions, respectively named main and top clamps and thought to be printed in PLA for its ease of print and better tolerance to flexion than ABS. This also allowed to add a guide on the main clamp to both protect and ease manipulation of the syringe.

3.3 Transmission shaft

Since the function of this shaft imposed a conventional machining, it was interesting to look for existing solutions from suppliers, like the DryLin® assortment of plastic linear bearing from IGUS. This provider was chosen for attractive prices and because of the availability of each items that could be grouped with a regular order of the Lab2Prod. The shaft is an aluminium square profile that plays the role of a rail on which a plastic bearing will be mounted. Both can support a torque up to 3000 N.cm that is way superior to the stepper holding torque, and the square profile was ordered with an extra margin to ensure its future integration in the overall design.

3.4 Motorisation and reduction

For this transmission with reduction gears were chosen over belt-based solutions because it was impossible to manufacture such solutions at the Lab2Prod. Then 3D printing the gears in plastic in the Lab2Prod offered a cheaper, faster and easier solution to redesign in case of mistake than conventional machining or ordering them. On top of that, high degrees of complexity do not affect prices, allowing to manipulate more efficient gearing shapes than with conventionally produced gears in the same conditions. Of course, printing gears using the available plastics is a sacrifice in surface finish and durability compared to injection moulded or machined plastic parts. But when designed correctly, printed gears can provide efficient and reasonably high load transfer. Considering that the original Lulzbot Mini FDM extruder also uses printed gears and regarding the relatively slow torques and speeds that will occur in the mechanism, printing gears was thus an ideal compromise in our case. Since it was possible to work with all range of gearing for the same amount of price and time, the choice of the main shape stopped on the herringbone. This presents the advantages of helical gears that allow more teeth to come into contact simultaneously to work more quietly than spur gears. Yet those helical teeth also create axial thrust force leading to problems concerning alignment of the gears. But the herringbone uses both right-handed and left-handed helical teeth to balance those undesired inherent forces, which gives it at the same time the peculiarity of being self-aligning. Finally, the choice of ABS as the printed material was made regarding their raw mechanical properties.

After the decision to realise this reducer with ABS printed gears, the idea was to reuse the same stepper as the previous FDM extruder and drive it with similar speeds to take advantage of its best performance range. To match the simplicity driven strategy, it was decided to design the mechanism with the minimal amount of gears, the driving one being the pinion directly attached to the stepper's shaft. tests combined with Solidworks® simulations allowed to choose an involute tooth profile with a pressure angle of $\alpha = 25°$, as the American standard, and an unstandardized module of 1.9. Besides avoiding backlash issues, this combination provides a good bulk / strength ratio that will thus allow a choice among a larger range of ratios. Those choices were comforted knowing that for 3D printing a 25° angle is a good balance of chunkiness and efficient motion transfer on a palm sized gear (Graham 2017), plus that original Lulzbot printed gears are using this same pressure angle with 9 and 47 teeth. Then a helix angle of 22° was chosen by comparison with original gears, also being a good compromise for the staircase effect. Then the idea was to pick prime numbers to obtain a homogeneous distribution of wear. The pinion will therefore wear faster than the wheel but is also easier to reprint and to access for replacement on the global mechanism. Finally, the ratio was determined as being a rational number that could also be a rational, to limit the errors while calculating the total reduction ratio when changing needle's gauge. The 4.7 ratio was then a good compromise regarding the overall LDM extruder volume.

3. 5 Syringe protection

Hypodermic needles are cheap thus considered as expendables, but since they are extremely thin they also are acutely fragile, especially for smaller diameters than gauges 23. A simple shock can badly bend them or damage the output surface and compromise the overall printing precision. Firstly, if the out printing end is impaired the paste will uncontrollably flow considering both speed, direction and sprawl changes. Then if the needle bends, the tool head end reference will be altered by changing its relative position to the bed level and modifying the X and Y coordinates, thus resulting wrongful building of the printed part. In addition to that, the necessary automatic bed-levelling process is also the first source of vertical shocks on the extruder and thus of possible needle's deteriorations. On the Lulzbot Mini for the FDM mode, this operation is realised thanks to an electrical contact between the nozzle and the metallic washers that are located at the four corners of the bed. The Z level is thus detected when the nozzle-washers contact closes an electrical circuit called the zero-volt sense that is wired with a harness on the hot end. Consequently, it was needed to consider a solution in order to both protect the needle while printing and provide the same auto levelling function as FDM for the LDM mode

The biggest danger for the syringe is to see its micrometric screw damaged by high torque applied on the motor shaft, with drastic consequences on material extrusion. In order to protect it, the simplest found idea was to insert a mechanical fuse between the square shaft and the top clamp. Regarding the small range of torque applied on the mechanism the easiest way to produce this fuse was to print it, knowing that it would also be easier to remanufacture if needed. After comparison of materials mechanical values, the ABS has been selected for its stiffness and its neat way of breaking. Another argument in favour of ABS was also its good printability, especially for small parts like this one, which will allow to limit defaults in printed surfaces to better control the location of the crack. In order to do so, the geometry was based on a cylinder to obtain an equally distributed stress in the surface to break and thus ease the dimension estimations based on printed ABS mechanical properties (Ultimaker 2017).

4 prototype manufacturing

This chapter focuses on the building phase of the prototype, from identification of the definitive printing parameters to the assembly of previously designed solutions to manufacture the functional LDM extruder

4.1 version 0.0

This very first version was designed at the same time as the theoretical documentations were led. In parallel of providing designs for the early tests Among those settings, the strength of parts at macro scale will mainly depend on the shell and infill properties, but considering cracks and local defaults the temperature and speeds will have a bigger impact. Those last settings can thus be adjusted in the case where the piece has localized weaknesses, but broadly corresponds to a good surface finish. Since ABS was chosen to realise stronger parts than PLA the infill percentage generally keeps the same values as the ones above, knowing that beyond 60% the mechanical properties only improve in very little amount (Ligon et al. 2017). In addition to this, the risk of print crashes increases significantly because of layer cooling that is then more difficult to manage.to determine decent printing parameters ranges, its purpose was to gain a maximum of knowledge about printed parts mechanical properties to win time on design of the parts to be printed

4.2 versions 1.X

Those versions embody the development of the whole prototype, with cyclical improvements on the LDM mechanism and successive adaptations to the Lulzbot Mini frame, until printing of a fully functional version. The first step in version 1.1 was to make sure every sub-solution could be correctly inserted in the LDM extruder body and that this body fits perfectly to the X carriage, before printing the prototype. To do so, the first adaptation was to redesign the bottom body so that its shape better fits the one of the X carriage and avoid eventual collision due to fastenings positioning. The second one was to create accurate fastenings, with adapted nut caps to ensure the tightening of the M5 bolts imposed by the previous tool head fasteners to the X carriage. Then the automatic hole dimensions were adapted to all other M3 screws to create the attachment points of the body connections to be adapted, as well as an anchor to attach the main clamp centrally to the X carriage. The goal here was to create better anchor points for the body supports while improving the rigidity of the whole extruder by fixing it to two perpendicular surfaces of the X carriage. The second adaptation concerned the main clamp, whose first design had geometrical errors on the closed position. Those errors led to a badly deported angle that caused problems for the positioning of the syringe’s axis of revolution in the whole extruder and weakened the closing strip. That was solved by deporting the hinge on the two parts of the clamp. After a test of the first version, the printed dimensions were measured and compared to the CAD ones to better adjust the clamp diameter to the syringe’s nut. This trial has also highlighted some roughness in the hinge, which have been corrected by chamfers and larger slacks in version 1.1. It also allowed to change outer diameter dimensions to fit to the previously determined wall thickness to obtain a good strength / flexibility ratio for the tightening function. Those dimension adapted, the anchor strip for the fixation with the bottom body was designed.

4.3 Functional prototype

Because version 1.3 improvements were done during the first prints, the current functional prototype is a hybrid version made of large components from 1.2 on which are attached the latest sub-solutions updates from 1.3. Parts are still in production at the moment with a focus on print quality, to successively replace pieces that are already assembled and come to the entire 1.3 version. The figure 4.1 shows the currently used prototype and the CAD of the full next version

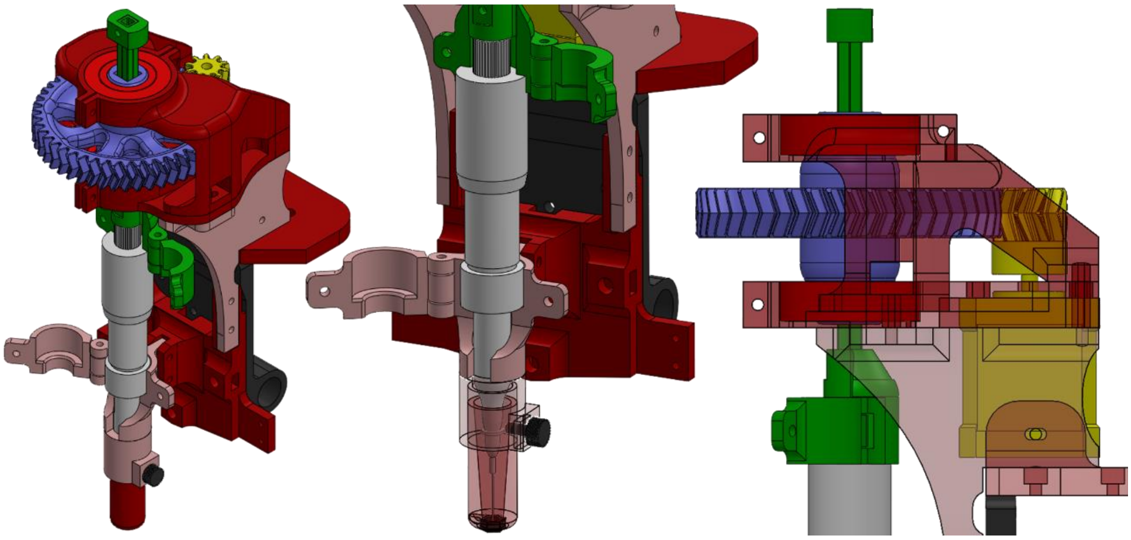

Figure 4.1 : 1.3 CAD version, next upgrade of the currently manufactured prototype

4.4 Testing and validation of the rig

After succeeding driving each element separately, the second test was to bring everything together in movement with a succession of gCode commands to ensure the layer printing protocol. As displayed on Figure 4.2, that was done by extracting shampoo, which has a more homogeneous composition and is consequently less viscous than the ceramic suspension. The drawn lines are placed in diagonal compared to the axis alignments and shows a constant thickness. This proves the ability of the rig to extract liquid at constant speed while traveling on both X and Y axis, which answers the requirements of ceramic paste printability testing. Another observation concerns the use of two different needles with cut bevels, where the quality of extraction did not present major observable differences with shampoo. However, inequalities might appear with ceramic paste but this factor can be overlooked by working with needles directly ordered without bevel. A problem related to shampoo bubbles in the syringe's reservoir also appeared after emptying half of the capacity. Contrary to the one displayed, this led to an inconstant flow of extracted fluid. As it could be a problem for future tests, it is thus recommended to load the ceramic paste by avoiding bubbles at the maximum. Finally, the printing end was manually placed on the bed thanks to the Lulzbot Cura controls, the layer height being visually placed with successive steps of 0,3 mm since there are no stop sensors on the Z axis positive direction. Then the automated movement of the machine were driven by the gCode displayed on the figure.

As an outcome, we can say the currently assembled version of the experimental rig fulfils the first function of fluid materials testing and allows mastery of X and Y directions, amount of extruded material and speeds while printing. However, it does not provide the overall functions of the FDM hardware, as for instance the auto-levelling. In that sense it is not ergonomic to use and a few improvements needs to be made both on the printed parts design in version 1.4 and on the software approach of the LDM printing process.

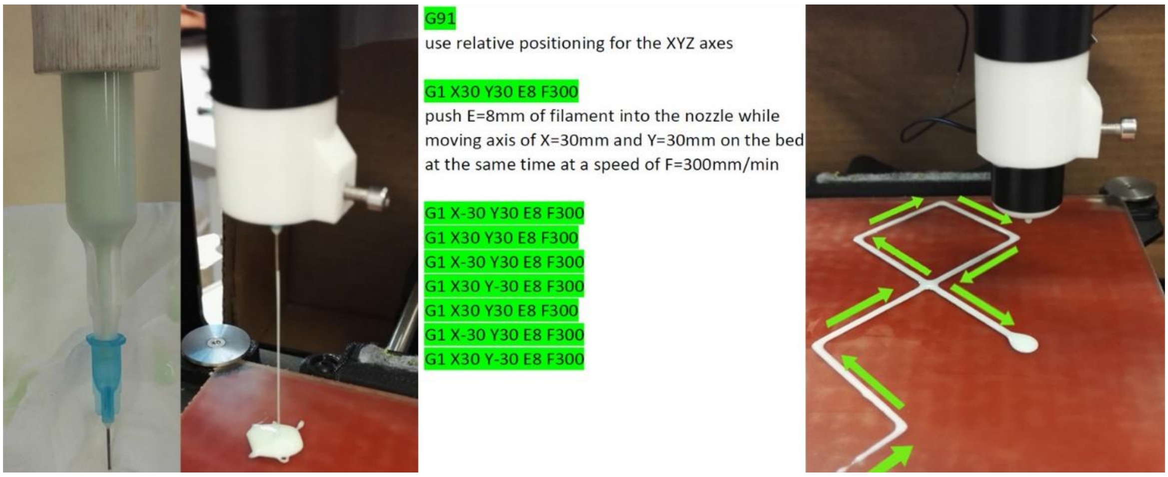

Figure 4.2 : Experimental Rig printing test

5. Conclusion

The developed machine could find a multitude of use regarding the needs in the medical fields, particularly in dental applications where the use of ceramic materials is increasing. Those are usually costly elements, hard to produce with conventional machining, and the few additive manufacturing technique they can work with are still limited or expensive to use. The created experimental rig has therefore shown ability to operate with a zirconia-ceramic paste produced by the partner BioMat Research Group, thus fitting in the needs of testing better dental materials in the long run. If the flowing speed of the early version of the ceramic paste was not mastered, on the other hand the positioning and printing speeds were.

This LDM experimental rig was build adapting an existing FDM printer by replacing its tool head. The developed tool head works thanks to a standard micrometric syringe, which sleeve is actuated in rotation thanks to a geared interface actuated by a stepper. The necessary modifications were designed using as much of the original machine's elements as possible, along with a maximum of 3D printed parts that were directly produced in the Lab2Prod. However, some parts were produced with available equipment for logistical reasons but their production was not justified from a cost study. Following a modularity concept for its assembly, it also possible to replace with ease specific part on this prototype, both for maintenance and printing process improvements. Along with the prototype, sub-solutions and solved problems were individually documented on parts design, forming a reliable process of designing for additive manufacturing.

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