Design and implementation of 3D printer for Mechanical Engineering Courses

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Abstract

Nowadays 3D printing is a hot topic and this was specially observed during the COVID-19 pandemic. Hence, this project has the objective to present the design and implementation of a 3D printer, which fits the Mechanical Engineering Courses requisites. The founded solution follows the Delta architecture and it was called Delta MAPL. This paper will summarize all important definitions and knowledge to build a 3D printer such as, 3D printers technologies and architectures, expose the developed project involving mechanic and electric project, project cost, programming and slicer, calibration, printing parameters, and will also expose de results through implementation of the project, 3D printing tests, and also the documentation with all design parts, codes and printing parameters. Therefore, 3D printer is very useful and involving many fields of Mechanical Engineering knowledge, thus 3D printing develops not only knowledge in mechanic, electric, sensors and actuators and material properties, but also creativity and problem-solving that are so important for all engineering students.

Keywords: Delta 3D printer; Mechanical Engineering Courses; Delta MAPL.

1. Introduction

Nowadays, the new Industry revolution, usually called Industry 4.0, refers to the emergence and diffusion of a range of new digital industrial technologies as Internet of Things (IoT), Big Data and Analytics, Robotic, and Additive Manufacturing (3D printing). On this way, the 3D printing has lots of advantages, such as, it is more available than traditional manufacturing, the products can be more customized compared to traditional process, it has relatively easy production of complex parts, it also has little or no waste of raw material, and the processes can be reversed as others additive process by remelting the material with the filament shape. However, there are some issues, such as, higher production time, inefficiency, higher cost, lower precision, lower resistance mechanic and thermic, comparing to subtractive processes (Strange and Zucchella, 2017).

For this reason, diverse enterprise and communities investing in 3D printer (Stratasys, Markerbot, Prusa and RepRap), 3D slicers (Simplify3D, Cura, and IdeaMaker) and repositories of parts (Thingiverse, CGTrader and Cults) for industrial and domestic users.

Due to COVID-19 pandemic the use of 3D printer increased. Many open-source designs of medical equipment and personal protective equipment (PPE) were developed by communities for combat against COVID-19, by printing protective masks, face shield, ventilator systems and valves (Belhouideg, 2020). These parts can be manufactured anywhere that have a 3D printer available, so it is ideal for small, diversified and local production (Strange and Zucchella, 2017), furthermore, 3D printing can reduce the burdens of trade tariffs and transportation costs (Laplume et al., 2016).

To accelerate the development of 3D printing, RepRap was created in 2005. It is a community to develop self-replicating manufacturing machine, normally use lots of 3D print parts and low-cost material to build this 3D printers, the projects are open source, so, it is freely available for anyone. They say that “the most important thing you can print in a 3D printer is another 3D printer” (RepRap, 2020). This project follows RepRap’s project, therefore it is open source and easy replicable, too.

On this way, there are lots of ‘Do It Yourself’ (DIY) 3D printer kits to buy, and the user can build his/her own 3D printer. This is one of the lowest way to buy a 3D printer and a good way to learn how it works (Best DIY - All3DP, 2020). A survey answered by teacher who use 3D printer in the classroom inform that the students developed many skills while working on 3D printing projects, including 3D modeling, creativity, technology literacy, problem-solving, self-directed learning, critical thinking, and perseverance (Trust and Maloy, 2017).

In addition to these skills, the use of 3D printers on the engineering courses is important to aid the extensions project to develop their projects and to assist the students on the Computer Aided Design (CAD) classes. Furthermore, the study of the use and how this machine works involves many engineering subjects which can help in the education of the student, such as, manufacturing processes, metrology, elements of mechanical construction, kinematic system, power transmission, electric, sensors and actuators, heat transfer, thermoplastic, mechanical properties, mechanic of solids, among others.

This paper will present the main concepts to know to develop a 3D printer in the bibliographic review. After that, the methodology will explain how this project was developed through the requisite analysis. The chapter of 3D printer design explains the specification of the printer, presenting the mechanical and electrical project, necessary components, programing, calibration, and total cost of this 3D printer. In the next section it is showed the implementation of the 3D printer, its tests, and the open documentation for future improvements of this project.

The main objective of this paper is to develop the design and implementation of a 3D printer to illustrate all the engineering areas that are essential to learn and how this new technology can aid in the process of education in diverse engineering courses, especially in the in aeronautical, mechanical and mechatronic courses. This paper will not have a focus on the 3D printed parts accuracy and quality surface.

2. Bibliographic Review

2.1 Additive Manufacturing

Additive Manufacturing (AM) is a technique of manufacturing which use CAD to build objects layer by layer (ASTM, 2020). There are seven categories according American Society for Testing and Materials (ASTM) and many technologies as Table 1 shows.

Table 1. Categories of additive manufacturing according to ASTM. (Nazir *et al*, 2019)

Categories	Technologies	Advantages/Drawbacks
Vat-Photopolym-erization	▪ SLA ▪ DLP ▪ CLIP	• High Building Speed • Good part resolution • Overcuring, scanned line shape • High cost for supplies and materials
Material Jetting	▪ Polyjet ▪ MJP	• Multi-material 3d printing • High surface finish • Low-strength material
Material Extrusion	▪ FDM ▪ FFF ▪ ADAM	• Inexpensive extrusion machine • Multi-material printing • Limited part resolution • Poor surface finish
Binder Jetting	▪ MJF ▪ SPJ	• Full-color objects printing • Require infiltration during post-processing • Wide material selection • High porosities on finished parts
Powder Bed Fusion (PBF)	▪ SLS ▪ SLM ▪ DMLS ▪ EBM	• High accuracy and details • Fully dense parts • High specific strength • Powder recycling • Support and anchor structure
Directed Energy Deposition (DED)	▪ LENS ▪ EBAM ▪ LMD-w ▪ WAAM	• High deposition rate compared to PBF process • Repair of damaged/worn parts • Functionally graded material printing • Require post-processing
Sheet Lamination (SL)	▪ LOM ▪ UAM	• High surface finish • Low material, machine, process cost • Decubing issues

SLA stereolithography, *DLP* direct light processing, *CLIP* continuous liquid interface production, *MJP* multijet printing, *FFF* fused filament fabrication, *ADAM* atomic diffusion AM, *MJF* multijet fusion, *SPJ* single-pass jetting, *DMLS* direct metal laser sintering, *LENS* laser engineered net shape, *EBAM* electron beam AM, *LMD-e* laser metal deposition with wire, *WAAM* wire arc AM, *LOM* laminated object manufacturing, *UAM* ultrasonic AM

Among these technologies, one of the most prominent are FDM (Fused Deposition Modeling), SLA (Stereolithography) and SLS (Selective Laser Sintering). All of them have advantages and disadvantage when comparing dimensional accuracy, time printing, cost, surface finish and mechanical properties. These features are presented in next subsections.

2.1.1 3D Printer's Technologies

2.1.1.1 FDM

This is one of most famous 3D printer technology. This mechanism is very simple, its similar to the hot glue gun. A filament of polymeric material is softened and melted with the aid of heat and is extruded, so, the material is pushed and forced through a nozzle of reduced diameter and then deposited layer by layer on the building platform or bed (Calignano *et al.*,2017), as shown in Figure 2. The filament has usually a standard diameter of 1.75 mm or 3 mm and it is supplied by a filament spool which can use many materials such as Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), Polyethylene Terephthalate Glycol (PETG), carbon fiber and nylon.

This technology has lots of benefices, it is simpler, the printer and the material aren't expensive, normally shorter time to print and to configure the machine, and many possibilities of material with different properties (Choudhari and Patil, 2016) (Sculpteo, 2020). Although the surface finish and dimensional accuracy is not got.

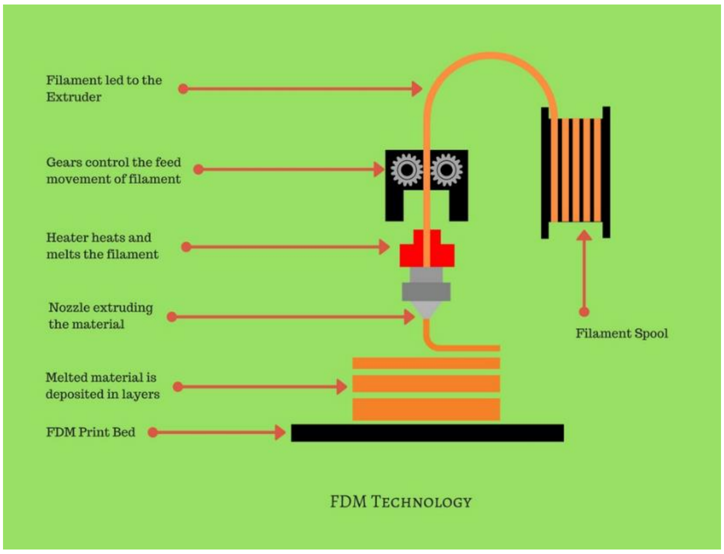

Figure 2. FDM mechanism of printing. (Manufactur3D,2018)

2.1.1.2 SLA

Similar with FDM, this technology also builds the object layer by layer by making 2D drawings. Therefore, these layers are built with a UV laser which will solidify a liquid photopolymer resin which is photosensitive (Sculpteo, 2020) (Gibson *et al*, 2010), as shown in Figure 3. This is the best technology for high surface finish and dimensional accuracy; however, the resin can be very expensive and normally has fragile fracture (Choudhari and Patil, 2016) (Sculpteo, 2020).

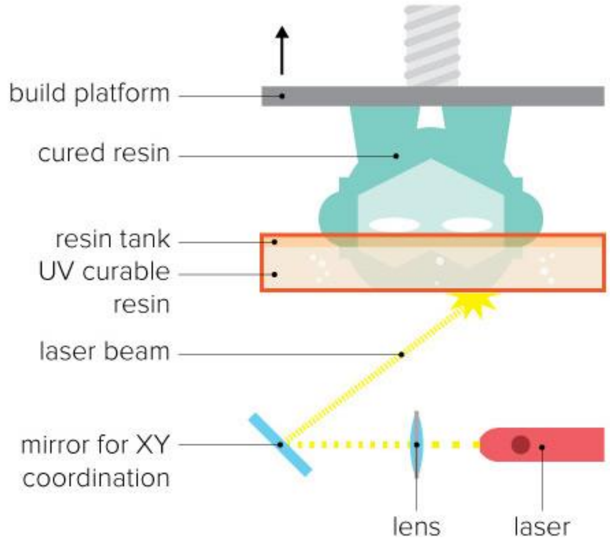

Figure 3. SLA mechanism of printing. (3Dream, 2021)

2.1.1.3 SLS

This technology is usually reserved for professional companies. The idea is also generating the part layer by layer by making 2D drawings. However, this time the laser will sintering together powder particles in the shape of the cross-section by heating and the building platform will go down for recover with other layer of powder (Sculpteo, 2020) (Gibson *et al,* 2010) (Legutko,2018), as shown in Figure 4. There are many advantages, for instance highest durability of the parts, lots of options of materials and it doesn't need to use supports. Therefore, the cost of the 3D printer is very expensive and the system is more complex. (Choudhari and Patil, 2016) (Sculpteo, 2020).

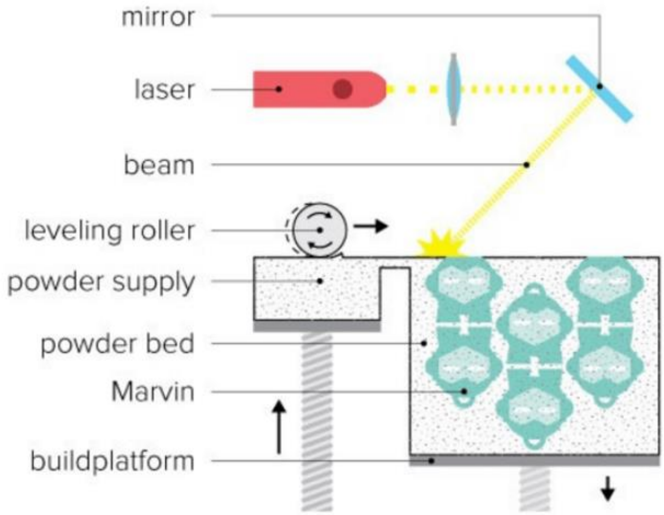

Figure 4. SLS mechanism of printing. (3Dream, 2021)

2.1.2 FDM 3D Printer's Architectures

Normally the FDM printers are classified in reason of the mechanical system and kinematic, there are lots of 3D printer types, for example: Cartesian, Delta, CoreXY, H-bot, polar, SCARA, and belt (O'Connell, 2020). The three architectures most found are Cartesian, COREXY and Delta, hence, the focus will be in these models. The comparison between these printers is hardly found in articles. Nevertheless, there are many sites and forum of 3D printer that make this comparison.

The Cartesian model has the X, Y and Z controlled separately like in the Figure 5 are called Cartesian. Thus, it uses normally one motor for X axis, other motor for Y axis and two motors for symmetry in Z axis. Due to this independent of each axis, it has the easiest calibration, assembly and found troubleshoot in sites and forums. Nonetheless, it is the most limited architecture, lower limit speed of printing, more vibration and inertia, and impossibility to print tall parts, due to the movement of the printing bed in Y.

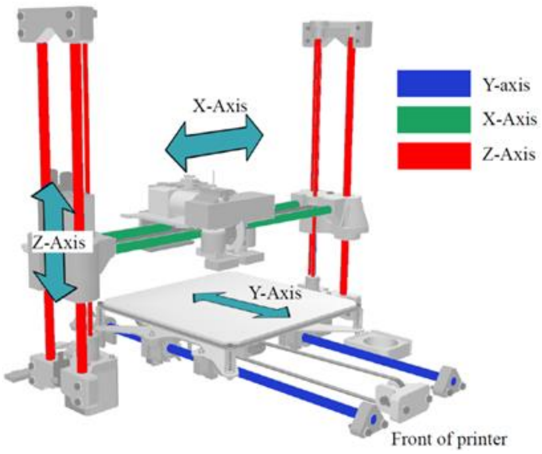

Figure 5. Illustration of Cartesian printer. (Cartesian3D, 2019)

The COREXY is very similar with cartesian, however the Z movement is due to the movement of the bed by two motors and the X and Y axis movements are determined by the control of two motor which works together by a belt association (Figure 6). Each belt color (Figure 6) is associate with your respective motor. Is a good printer to work in the XY plane, high printing speed, can print higher parts than cartesian due to the only Z movement of the bed. However, is the most expensive one in reason of the necessity of a more robust structure and more rigid table due to the vertical movement, moreover, the process of calibration is more difficult than Cartesian, because there are two motors which works together.

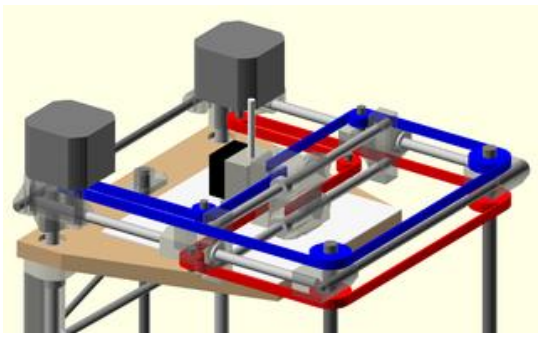

Figure 6. Illustration of COREXY printer. (CoreXY - RepRap, 2020)

Among the three architecture the most different kinematic is the Delta one. the movement of X, Y and Z axis is due to three motors, one in each tower which work together to move the axis in vertical, as illustrate in Figure 7. This structure is the simplest, use only three motors for movement instead of four, as the others models. Enable to print tall parts due to its height and the static print bed. Moreover, this kind of printer is easily extended in Z direction without redo the project. Can move in Z direction faster because it doesn't use thread bar or spindle. The move system is lighter, because it only uses delta arms, the hot end and the effector, so it results in lower inertia, enable high printing speed and use stepper motor with less torque. Furthermore, this structure takes up little horizontal space, making it easier to position it. However, due to this different kinematic, this is the most difficult architecture to calibrate and fix problems, it is worse to works in XY plan, and has a small 3D printer area by reason of circular bed.

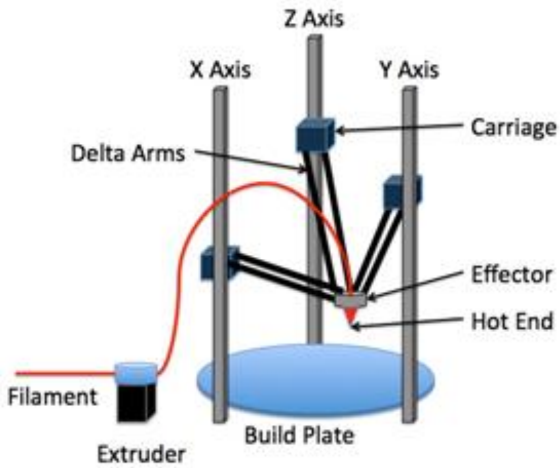

Figure 7. Illustration of Delta printer (Bell, 2015).

3. Methodology

3.1 3D printer Requisite analysis

The aim of this project is to develop one machine which can be used by the Mechanical engineering courses to improve the student knowledge and aid the implementation of many projects. Thus, it will be necessary the use of one kind of manufacture which is relatively cheap to implement, produce very complex parts at low cost, allows rapid prototyping for customized parts and small batches, it can be achieved by the additive manufacturing (AM) (Attaran, 2017).

There are lots of AM technologies, however, for this project was chosen the fused deposition modelling (FDM), by reason of it provides a range of raw material with different mechanical properties for many applications, it is cheaper compared with the other technologies, and the process of fabrication is relatively simple (Calignano *et al.*,2017).

To choose the type of the FDM printer it necessary to establish the requirement of this project. It will be analyzed the cost of printer with the same printing volume, printing time, printing accuracy, superficial quality, printing volume in relation with printer volume, facility to calibrate and fix problems and facility to enclosure the structure.

With the aim of choose the best printer to build for the conditions of this project, distinct weights for each factor were assigned. The cost is the most relevant so the weight is five, printing time, accuracy and superficial quality are very important so the weight is three, and the other factors are less reelevates for the aim of this project, so it was given one.

The color of each factor for each printer is in reason of the advantages, the green is the best and will score five points, yellow is the intermediary and will score three points, and the red is the worst and will score one point. The final score of each printer is the sum of all color point multiplied by their weight. All these characteristics were analyzed based in the experience of the MAPL (Manufacturing Automated Planning Laboratory), information on the internet and articles in the literature.

The cost of printer with the same printing volume is the most important, because if the printer is cheaper the university can build more machines for the education laboratories. The COREXY is the type the most expensive to build and to buy due to the necessity of high structural stiffness, in comparison Cartesian has a simple structure and Delta uses one motor less and has less components made them cheaper. Printing time is another crucial parameter, because normally 3D printers are not fast and the long printing spends hours. Delta and COREXY allow faster printing due to lower inertia of the carriage beyond static bed for Delta and only slow vertical movement of the bed for COREXY, it gives less vibration in faster printing. Accuracy is so important in mechanical projects to guarantee clearance or interference fits. Due to three conjugate motors for Delta and two for COREXY, the geometry of the structures needs to be most near of a square for COREXY and equilateral triangle for Delta. Thus, the tolerance of the components used and the assembly process interfere in the accuracy manly for Delta after for COREXY. The superficial quality is verry important to reduce energy losses due to the friction, smooth 3D printing avoids the necessity of a superficial finish. Due to the less vibration in COREXY and Delta the pieces are smother. (O'Connell, 2020) (Creality, 2021) (Tractus3D,2020) (Sampaio, 2017) (Fabbaloo,2020) (Schmitt *et al.*, 2017)

Besides that, printing volume in relation with printer volume is important to reduce the volume the printer occupies in the lab. Cartesian has the worst relation due to the horizontal bed movement, after COREXY because of robust structure and Delta is the best because the it occupies a low area on the floor or on the table and it is tallest. The calibration and fix involve, mechanical and electrical fix besides mechanical calibration and calibration by software mainly for stepper motor and end stop sensors. The cartesian is the best due to simple kinematic and large troubleshooting on the community. The COREXY, Delta is more difficult to calibrate due to conjugate motors system as explained in accuracy problem. Lastly, the facility to enclosure, enclosure the printer is important to imprint material which have high retraction when cooled, enclosure can avoid warping problem and improve the superficial quality. The COREXY is the easiest to enclosure due to the cubic geometry, after Delta because of towers, and Cartesian normally needs to build a full box to enclosure it. (O'Connell, 2020) (Creality, 2021) (Tractus3D,2020) (Sampaio, 2017) (Fabbaloo,2020) (Schmitt *et al.*, 2017)

Among the three models is possible to see that Delta reach the highest score (67, as presented by Table 2) with this specific requisite analysis. Which the cost, printing time, accuracy and superficial quality are the most important paraments. In other application for example when the cost isn’t so important, the COREXY is a good choice. And when the focus is a cheaper printer and easy printer to use the Cartesian is a good choice. Hence, the decision of the best printer depends on the application and the desired requirements.

After choose the 3D printer architecture is possible to start the development of the 3D printer project with the Delta type, called Delta MAPL.

Table 2. Comparative of requisite analysis between Cartesian, COREXY and Delta.

Printers	Cost (5)	Printing Time (3)	Accuracy (3)	Superficial Quality (3)	Printing Volume/Printer Volume (1)	Calibration and Fix (1)	Enclosure (1)	Score
Cartesian	Cheaper	Slower	Good	Less Smooth	Smaller printing area and cant't be height / Big printer area	Simple and Large Comunity	Harder	53
COREXY	Expensive	Faster	Depends on the assembly	Smooth	Big printing volume / Big printer volume	XY conjugate motors (perfect square)	Easy	55
Delta	Cheaper	Faster	Normally vary in priting bed	Smooth	Smaller printing area tall height / Small printer area tall Height	XYZ conjugate motors (perfect triangle)	Medium	67

4. 3D printer Design: Delta MAPL

4.1 Structural Project

To develop the structural project is necessary understand de kinematic of the Delta printer. The relation between the speed of each tower and the speed in cartesian axis X, Y and Z is found in the literature and is a complex matrix which depends on the position of each tower and the size of the printer (Williams, 2016). Furthermore, it is important to know that how far the printer is in relation of the center of the bed, lower is the angle of delta arm with the horizontal resulting in faster speed due to the kinematic, causing instability and losing accuracy. Hence, it is important to know that to know the limit of movement of the printer (Delta geometry - RepRap, 2019). By this reason the minimum angle was defined as 20º to limit the multiplier of speed in 2,75, as shown in Figure 8.

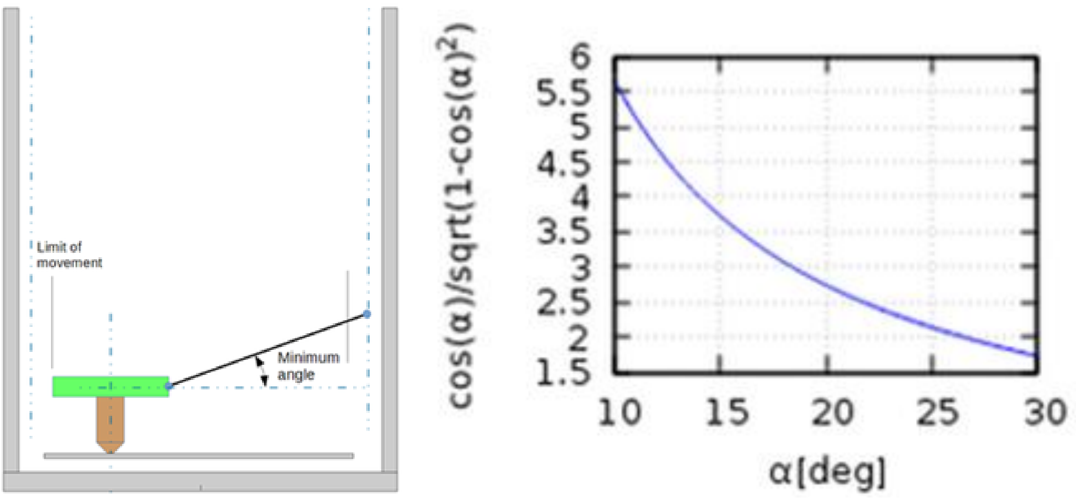

Figure 8. Relation of the angle of the arm and the multiplier of speed (Delta geometry - RepRap, 2019).

The delta heat bed has 22 cm of diameter but only 20 cm of heat zone. Applying the minimum angle as 20º the useful diameter will be 17 cm. Besides, the height of the printer is defined to achieve the printing volume with a cylinder with 38 cm of height and a cone on the top with 2 cm of height, as shown in Figure 9. This cone zone is not good to print because the arm may hit the top of the printer. For this reason, the printing volume considered is the cylinder with 38 cm of height and 8,5 cm of radius resulting in 8625 cm^3.

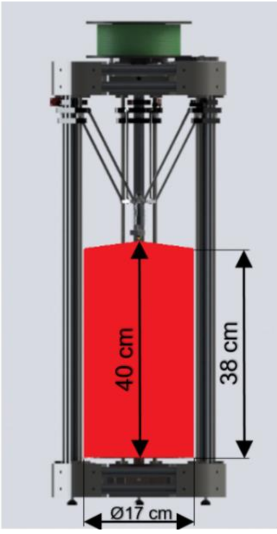

Figure 9. Printing volume of the Delta MAPL

After define the printing volume the CAD was developed, the first version of the printer has only aluminum profile in the tower and the bottom and the top are aluminum plate, however the stiffness of the aluminum plate is not high besides it is expensive to buy this plate cut by an CNC (Computational Numerical Control). Thus, it was done many changes to increase the stiffness of the structure without increase the price as shown in Figure 10.

This final version has two aluminum profile with 20 mm x 20 mm and they have a distance to increase the momentum of inertia, this solution is more rigid and has a close price than use just one 30 mm x 30 mm aluminum profile. Furthermore, all corners of the triangle are 3D printed and can be printed in other printers, the motors of the tower are hidden on the bottom besides the structure is more compact in area and height. To guarantee the linear movement of the carriage at the tower it was used two smooth rods for each tower and a linear bearing was placed in the carriage (Figure 11). Theses smooth rods also increase the stiffness of the structure. It was used a screw that went through the corners parts to guarantee the fixation of the parts in addition to preventing the pieces from breaking by shearing layers.

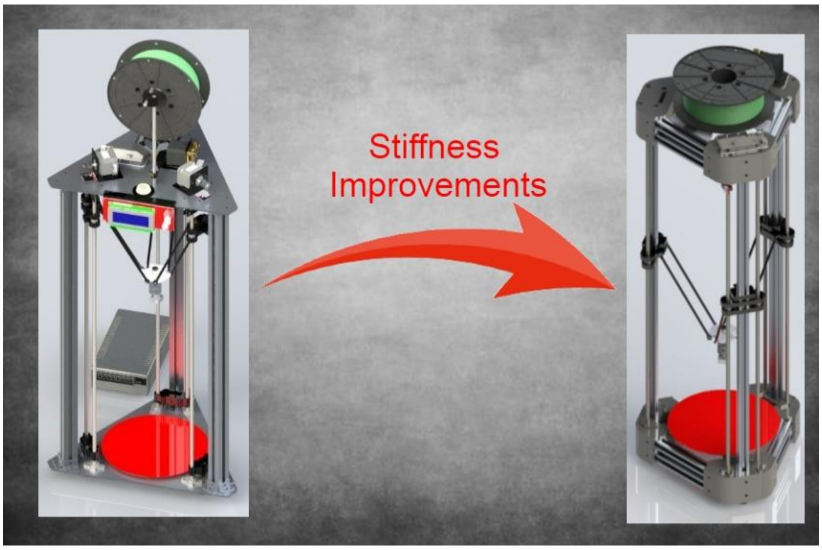

Figure 10. First version and last version of the Delta MAPL with stiffness improvements.

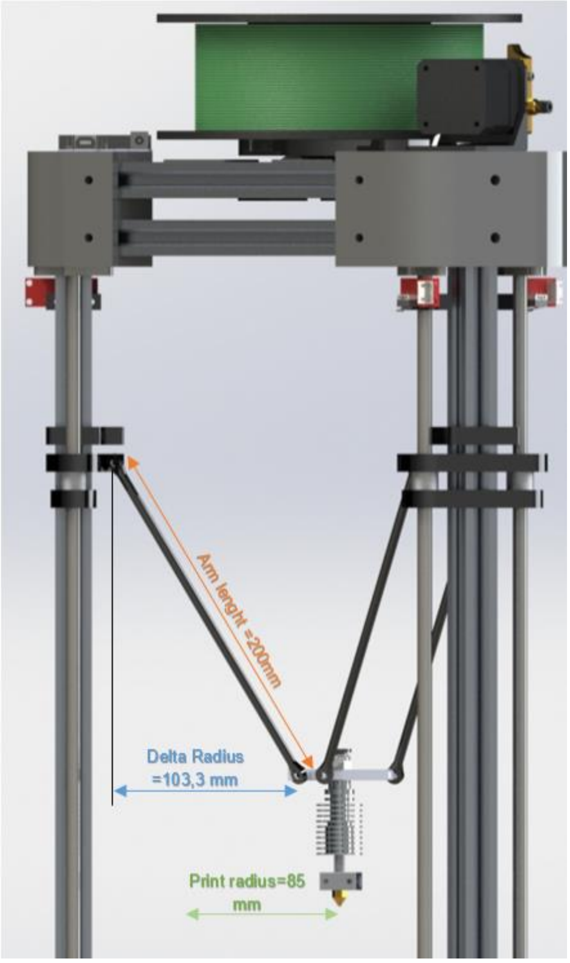

Figure 11: Relevant dimensions for internal calculation of printer kinematic

To adjust the tension of the belts which promotes the carriage movement it was developed as simple system which can vary the length of the belt by adjusting two screw (Figure 12). Moreover, the most used screws in this 3D printer have been the allen type, because this screw can be adjusted in locations of difficult access.

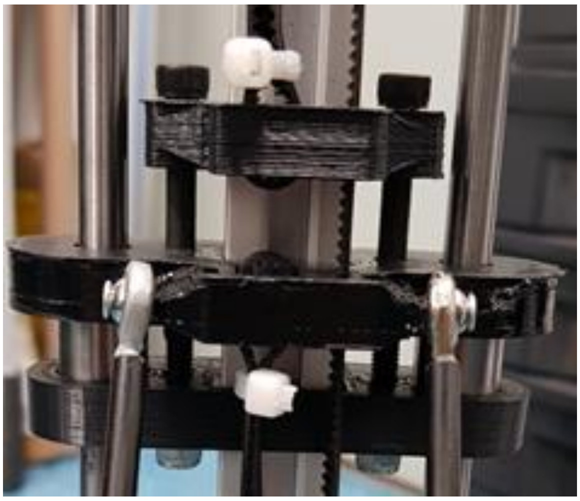

Figure 12: Adjusting tension system developed.

4.2 Electric Project

The electric project independently of the architecture of the printer is very similar. Normally is used the microcontroller Arduino Mega 2560 which is compatible with the firmware *Marlin* and a shield called RAMPS is used to aid connect the other electric components, as shown in Figure 13. In this case it was used the RAMPS 1.4.

In the wiring illustration of this 3D printer, it is possible to observe many components, there are four stepper motors which are responsible to promote the movement of the carriages of each tower and the extrusion of the filament, each motor needs a driver to aid in the control of the motor and enable the microsteps movements. There are three end stop sensors, one for each tower to inform the origin of the system and the max range in Z direction.

Furthermore, there are the heater extruder (hotend) which will melt the filament. There are two fans and their function are to cool the hotend and the RAMPS. Moreover, there are the heater bed that function is heat the bed. There are two thermistors to measure the temperature of the hotend and the bed. Finally, there are a switching power supply to give the energy for components.

Due to high current demanded by the bed heater it was used Heatbed HA210N06 MOSFET Module connecting the switching power supply to the bed heater (Figure 13), to reduce the energy in the RAMPS. In this illustration there is one LCD monitor which hasn't been used on this project; however, it can be implemented further, because the LCD enable print objects without the computer, use only a SD card.

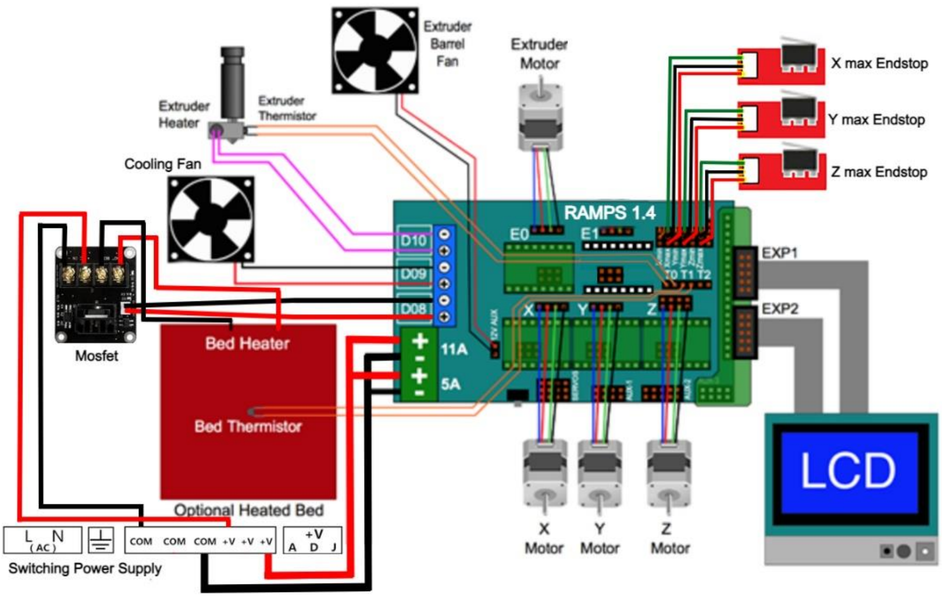

Figure 13. Electric wiring diagram of the printer.

4.3 3D Printer Cost

After defining all mechanical and electrical components it is possibly present the total cost to build the DELTA MAPL 3D printer. The Table 3 below has the cost including the shipping of all components, it also has one 1 kg of ABS which will be used to make the printer test and 2 kg of ABS to print all printed parts. The total cost of around R$ 2,000.00 is lower than another printer with the same printing volume in Brazil.

Table 3. Costs of all used materials

Itens	Quantity	Cost with Shipping
3D Printed Parts	2 Kg	R$150.00
Aluminum Profile	4.848	R$164.57
Arduino Mega + Ramps + Drivers + LCD	1	R$169.86
Bearing 608zz x 10	1	R$47.89
Belt + 4 Pulley	1	R$87.90
Delta Arm x 6	1	R$71.51
Endstop	3	R$40.30
Extruder	1	R$66.80
Filament	1	R$104.84
Furniture Leveling Feet	3	R$6.00
Glass	1	R$15.00
HA210N06 Mosfet Module	1	R$52.35
Hammer Nuts	42	R$67.20
Heat Bed	1	R$88.35
Hellermann Cable Ties	10	R$5.00
Hotend + Cooler + Nozzle	1	R$61.90
Hotend Support	1	R$84.90
Linear Bearing Lm8uu x 6	1	R$42.80
Motor Support	1	R$37.20
Nema 17 Motor	4	R$239.96
Screws + Washers + Nuts	Many	R$45.00
Smoth Rods 700 mm x 8 mm x 6	1	R$114.90
Smoth Rods Support	12	R$133.29
Switching Power Supply 12 V 30 A	1	R$68.90
Threaded Bar M5 and M8	3	R$16.60
Wires + Heat Shrink Tube	Many	R$10.00
Total		**R$1,993.02**
US Dollar (US$)/Brazilian Real (R$)		**5.37**
Total		**US$371.14**

4.4 Programing and Slicer

It is important to know how the 3D printer works. For FDM printer the part is made in a CAD software, in this software the part is converted to STereoLithography (STL) format which is a surface of the object composed by many triangles. After that the user import this part to the slicer, and he can slice this part to generate the path of nozzle for each layer of printing. Following, the slicer generates the GCODE which is a language of CNC and inform to the printer in a text file all necessary information to print the object, as temperature of bed and hotend, speed of extrusion, and manly the coordinates of the nozzle, as illustrated in Figure 14.

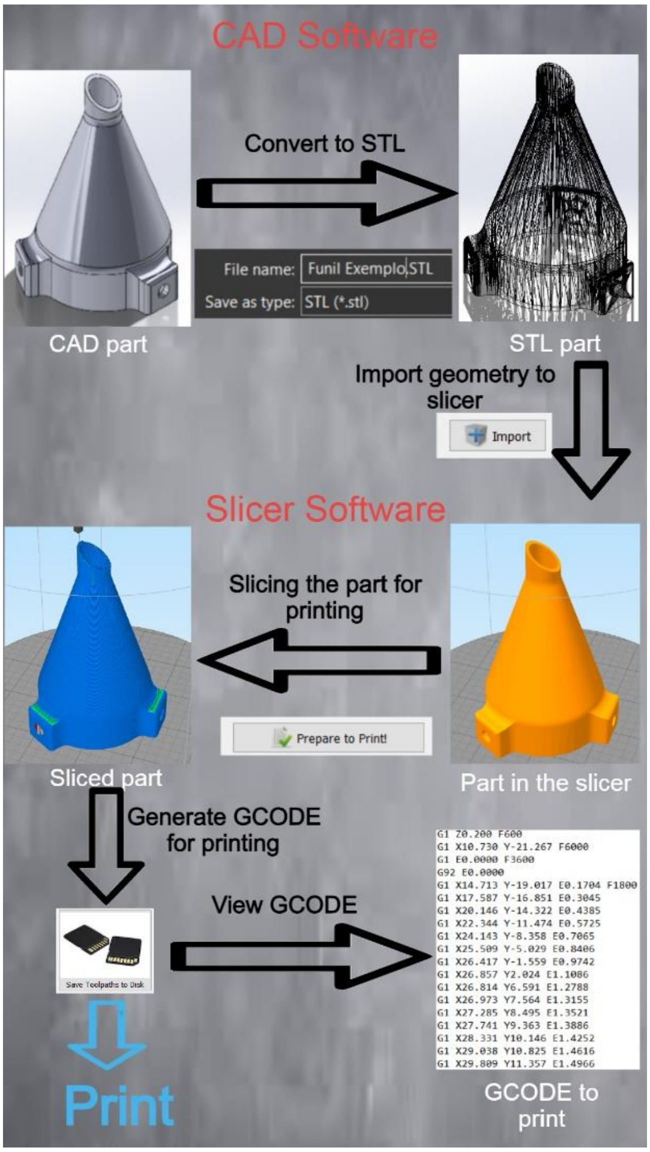

Figure 14. Schematic of how the slicer print a FDM part.

Programing the printer is a simple task, because there are many firmwares such as *Repetier*, *RepRap* and *Marlin*, they have all functions implemented and the user only need inform which functions he wants activate and give the parameters. In this phase the user informs, the printer type, the direction of rotation and step of the motor, the kind of thermistor, the dimensions of the printer, in this case of delta, arm length, delta radius and print radius (Figure 11), and other information. For this project the firmware chose was *Marlin* due there are more documentations and information in forums, besides that it has many GCODE functions and implemented functions.

Furthermore, it is possible to program a starting and ending script by GCODE to make the printer repeat this task all times after and before a printing. For this project the starting script the GCODE was implemented to configure the printer parameters of geometry, and the nozzle cleaning by a programed motion of the nozzle on the bed. For the ending script the GCODE was implemented to turn off the heater of the bed and of the hotend and disable the motors.

4.5 Calibration

Calibration is one of the most difficult phases for delta printer, because all motions in this architecture depends on the movement of all motors, besides that the motion of the printer is calculated based in the geometry of the printer. Thus, if the towers are not an equilateral triangle or the arms have different length or other variations, the calculated movement is not the real movement.

The simplest calibration process is the step/mm of the motor, this valor is normally informed by the user in the programing, but can be changed by GCODE after. This calculation is simple and depend on the motor step angle, the belt pitch, pulley tooth count and driver micro stepping. By the mechanical relations of power transmission, it is possible to result in the Equation 1 which can calculate the motor step/mm. There is a fine calibration to improve the accuracy of the printer, it is based in measure the external dimensions of a cube in X, Y and Z directions and increase or decrease the step/mm by the same proportion of the relation of nominal size and real size in each direction (Equation 2). But, for delta printer it isn't possible, because in delta the three motor must have the same step/mm, furthermore this fine calibration is not recommended because the user changes the theoretical calculated step/mm to another which depends only on the external dimension of the part.

$$Step/mm = \frac{360}{(Motor\_step\_angle * Driver\_microstepping) * (Belt\_pitch * Pulley\_tooth\_count)} \quad [1]$$

$$New_{step/mm} = Old_{step/mm} * \frac{nominal\_size}{real\_size} \quad [2]$$

Moreover, one of the most important calibration is the printing of the first layer, because the bed is a plane, but the real movement of a delta not ideal isn't regular due to the variations in the real geometry. To reduce this problem a set of three screws was placed to adjust the angle of the table plane. This is one of the most famous calibration. However, for delta it is not sufficient, the position of the three ends stop sensors change the kinematic of the printer. To solve this problem an offset of distance was made by GCODE with the function M666 to change the reference of the position of the end stop sensors. Besides that, to adjust the distance between the nozzle and the bad the height of the printer was set as 390.90 mm and to adjust the concavity of the nozzle motion the delta radius was set as 103.3 mm by the M665 command.

4.6 Printing Parameters

There are many printing parameters, and they vary with the used slicer. This is one of the most important tasks to print a part, because this is not only for a person who develops a 3D printer but also for those who buy a printer, besides that these parameters can change the mechanical properties of the part, superficial quality, printing time, accuracy and other factors.

The 3D printer parameters can change the flow of the material in the nozzle, are relevant, and these parameters may change with the material used to print. Thus, the hotend temperature is important because higher temperatures will reduce the viscosity of the material and will increase the material flow and will impact also in the adhesion of the layers, another important parameter is the printing speed, low speed can increase the superficial quality and the accuracy of the part and high-speed permit print the pieces faster but will demand a high material flow. Moreover, it is possible to increase the layer height and the width of the path, it will permit print the pieces faster, but with a worse resolution decreasing the accuracy and superficial quality. There are many other parameters to change but it is not the aim of this paper.

5. Results

5.1 Implementation

The printer was implemented as the expected in the CAD software (Figure 15). All printed parts were printed in ABS, the firsts parts were printed more than one time to adjust the clearance or interference fits between the parts. But after that was observed a systematic error in all holes around 0.25 mm than the nominal dimension, maybe in reason of the retraction of the material. To solve this problem all holes which cannot have an interference fit where increased in 0.25 mm. There is a function called horizontal size compensation but it is not recommended because it changes the external dimension too.

To reduce the quantity of wires outside the printer it was placed all wire of the motors and of the mosfet inside the aluminum profile to the RAMPS. Unfortunately, there are many wires in a 3D printer and disappear with most of them is really difficult, mainly in RAMPS.

It was implemented also a support for the filament spool with bearing on the top of the printer to reduce the energy losses (Figure 15). There is also the regulation of belt tension (Figure 12) and the regulation of the angle of the table plane by the rotation of the small white pieces in Figure 16. Moreover, due to the mechanical project the printer is verry rigid and has little vibration, this increases mainly the surface quality of the printed parts (Figure 15).

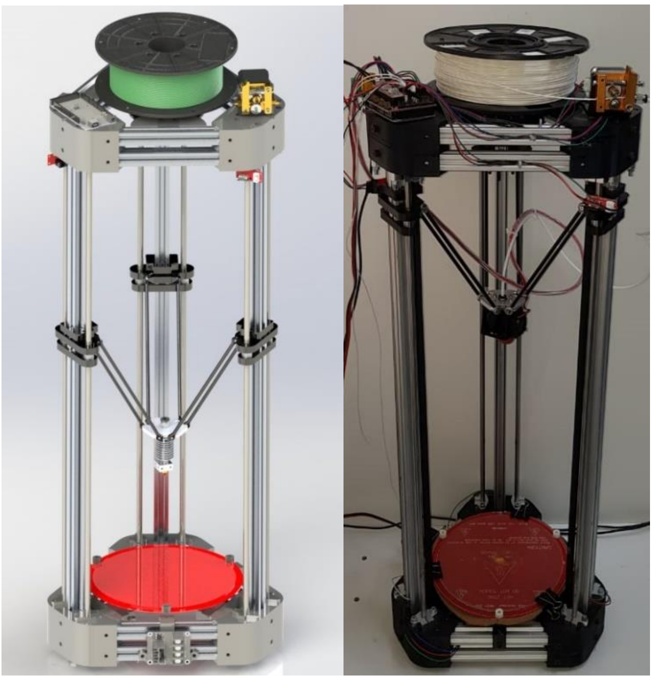

Figure 15. Final version of 3D CAD and the implemented project of Delta MAPL.

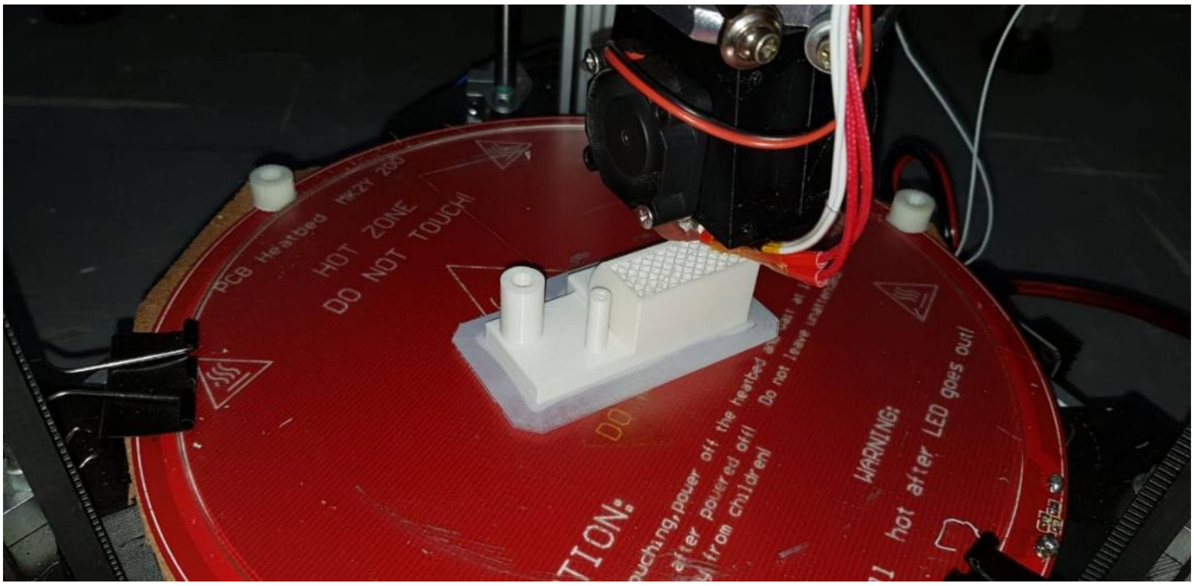

Figure 16. Deltar printer printing the test part.

5.2. Tests

To validate the Delta MAPL printer, it was used a printing test part developed in the MAPL with printing speed of 60 mm/s. This part has many different surfaces like a shaft, a hole, a curvature, and many planes (Figure17). This printing allows to analyze the surface quality and allows acquire different measures to analyze the accuracy. On this way the surface quality is verry smooth and the accuracy of the printer varies according to the measures, the biggest dimension of this part has 60 mm, the difference between the nominal and real dimension on the heigh and the diameter of the shaft if smaller than 0,05 mm, but for *X* and *Y* dimensions the error is greater and with an average of 0.50 mm.

These results of surface quality and accuracy was expected due to the non-ideal geometry of the printer and the information on the Table 1. But this accuracy error can be mitigated by using a sensor of auto leveling of the bed.

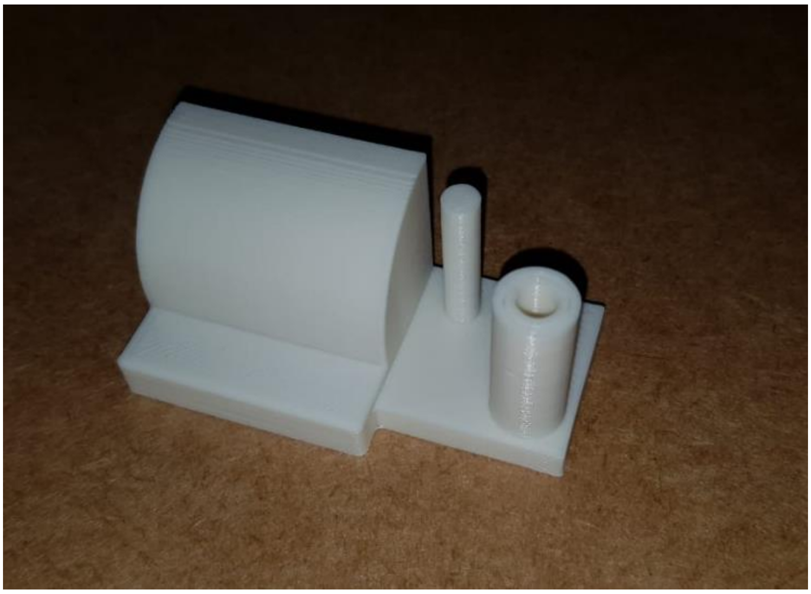

Figure 17. Printing test part for validation of the project

5.3 Documentation

The open-source projects of 3D printing have been crucial to the development of the technology. For this reason, all essential information of this project, such as CAD parts, configuration of slicer and *Marlin* code were shared in two open-source site of CAD projects and 3D printing parts, in GrabCAD (https://grabcad.com/library/delta-printer-mapl-1) and Thingiverse (https://www.thingiverse.com/thing:4562522) respectively. Thus, the community can implement this project freely and anyone can improve this project and reshare with the community, it is the best way for dissemination of knowledge of 3D printer and aid to improve this technology.

6. Conclusion and Further Works

The objective of this project was successfully achieved, which was design and implement a 3D printer for mechanical engineering courses. This printer can printing parts in a relatively short period of time with smooth superficial quality due to delta architecture, which promote the use in several application such as prototyping and final use parts. All developed parts and used codes and printing configurations are available in GrabCAD (https://grabcad.com/library/delta-printer-mapl-1) and Thingiverse (https://www.thingiverse.com/thing:4562522).

The development of this project involves many knowledges that are essential of mechanical engineering students, such as 3D modeling, manufacturing processes and heat transfer to drawing and manufacture the parts, besides elements of mechanical construction, kinematic system, power transmission to make the design and assembly of printer, beyond mechanical properties, mechanic of solids and material properties for increase the stiffness and optimize the parts, as well as the electric, programming, use of sensors and actuators to choose the best component for the application and make the connections and control of all these components. Furthermore, it covers other areas of knowledge not well developed in the engineering courses such as creativity, problem-solving and practical knowledge mainly in mechanic and electric.

For future works it will be implemented an LCD display and auto leveling sensor to make the experience with the user easier and improve the accuracy of the parts. Moreover, it will be implemented an enclosure structure with acrylic sheet to reduce the effects of warping in ABS parts, as well as the writing of a guide book for 3D printer users.

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